The Destructive Extent of the California Earthquake. Its Effect Upon Structures and Structural Materials Within the Earthquake Belt.

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Preface

THIS article was written to accompany a number of essays presented in book form under the title "The California Earthquake of 1906." That volume was edited by Dr. David Starr Jordan, President of Stanford University, who contributed also one of the essays. The work was published by A. M. Robertson of San Francisco.

The essays chosen were of different types, written by individuals with varying scientific or technical interests. The object of the editor and publisher was to arrange a series of articles which would give a clear, comprehensive and accurate account of the great earthquake and its associated phenomena.

One of the component essays, therefore, dealt with the engineering problem. As the publishers desired to reprint it separately, that essay is presented without change in the following pages. It is a description, written by an engineer, outlining the destructive extent of the California earthquake. It discusses the effect of the disturbance upon structures and structural materials within the earthquake belt.

To make the treatment complete, the lessons to be learned from the San Francisco conflagration should have been added. For want of time the author regrets that it has been impossible for him to make such an addition.

If these pages can convince the reader that our earthquake losses in large measure were due to a lack of honest or intelligent construction adapted to the needs of an earthquake locality, then have the publishers been justified in reprinting this essay.

CHARLES DERLETH, JR.

University of California,
April 18, 1907.

The Destructive Extent of the California Earthquake

ON the eighteenth of April, 1906, at 5:13 in the morning, one of the most severe earthquakes ever recorded since the beginning of civilized habitation visited the State of California. The important destruction to engineering works occurred in a belt about fifty miles wide and nearly three hundred miles in length, extending along the Pacific Coast, with the Bay of San Francisco at its center.

INTRODUCTION

Immediately after the earthquake the Governor of California, the Hon. George C. Pardee, established the California Earthquake Investigation Commission, which has diligently studied the scientific phase of the subject. The commission's preliminary report clearly outlines the general geological features of the earthquake belt and the important phenomena observed in the region of most violent shock. The commission has carefully studied time records to determine coseismal curves, and collected data for the purpose of establishing lines of equal severity or intensity of shock, that is,

isoseismal curves. As one of the conclusions to their work the commission will undoubtedly discuss the relation of earthquake effects to man and to human works, that is, engineering construction; but as that body consists mainly of pure scientists, namely, geologists, physicists, and astronomers, their work in the interpretation of the destruction to structures can not be complete without the co-operation of students of engineering.

Members of the San Francisco Association of the American Society of Civil Engineers have considered the engineering side of this large problem, and various sub-committees have reported detailed studies for different and distinctive types of construction, such as buildings, streets, harbor works, water systems, sewers, railroads, power stations, and foundations. These reports have been forwarded to the parent society in New York and have been printed in the March (1907) Proceedings of the American Society of Civil Engineers.

A local association given the name of the "Structural Association of San Francisco," consisting of engineers, architects, contractors and manufacturers of structural materials, with a purpose similar to that of the American Society of Civil Engineers, is also in the field. Its members, too, have appointed sub-committees for a division of labor in collecting and studying data in this vast problem.

The Structural Association is confining its attention mainly to San Francisco and the question of earthquake-proof and fire-proof buildings.

At this writing a report is in press, written for the United States Geological Survey by Messrs. John S. Sewell, Frank Soulé and Richard L. Humphrey, in which these gentlemen, all engineers, treat of the effect of earthquakes and fire upon structural materials.

Furthermore, many articles by engineers have appeared during the past year in the engineering journals, treating of the earthquake and fire problems. It is plain, therefore, that the subject is receiving considerable attention by those interested in building and in structural materials.

Engineers are concerned not only with the temblor's destruction, but also with the fire problem. Immediately after the earthquake, great conflagrations broke out in San Francisco and Santa Rosa. The earthquake meted out great destruction, and the large losses will be felt for some time to come; but there is always at least a little good accompanying evil, and all intelligent and honest builders have recognized that the calamity offers a great opportunity to compare the efficiencies of different types of design and to observe the relative behavior of different kinds of materials in their resisting qualities to withstand earthquake shock and retard the

progress of fire. It seems to me that the engineering problem is at least as large as that of the geologist; at any rate it is more important in its practical bearings, because it combines the study of structural stability with the theory of fire-proofing and must pay considerable attention to the relation of destruction of structures to geological formations.

From the purely scientific standpoint this earthquake presents perhaps the most favorable problem which it has yet been the privilege of seismologists to study, because the extent of the earthquake is so large, the area of destruction embraces such varied topography, and because the geological formations of the Pacific Coast are so striking and so unique. From the very first, the center or line of disturbance has not been in doubt, for a crack is visible on the earth's surface for at least 200 miles, and runs in an almost unbroken straight line along an old geological scarp. This scarp, or plane of crustal weakness, is plainly visible to the educated geological eye, and has been known to geologists for more than a generation. Again, the magnitude of the shock was so considerable that its vibrations were felt at many places quite remote from San Francisco. The tremors were distinctly felt in the southern part of California, in Oregon, and at several places in Nevada; while precise instruments

have recorded small crustal movements at Washington, D. C., in Germany, and at Tokyo. We have here a fruitful opportunity for an advance in the world's knowledge of geophysics, and scientists generally will look with anticipation to the final report of the California State Earthquake Commission.

For the engineer, from the purely applied science point of view, there is an equally wide opportunity. All kinds of construction and all kinds of material have been subjected to both stress and fire. Structures, good and bad, of able and deficient designs, of honest and criminal workmanship, all have been tested by various degrees of vibration, from the most severe shocks in the region of the fault line to shocks of much less severity for places resting upon firm foundations.

EARTHQUAKES AND CRUSTAL MOVEMENTS

The crust of the earth is constantly adjusting itself to conditions of stress and strain. The surface of the globe is gradually and slowly changing its form to suit these adjustments. The span of a human life is quite negligible in comparison to the geologic ages required to bring about marked deformations in the surface of the globe, and consequently many of us are not aware of the slow crustal movements which to the eye of the experi-

enced geological observer are everywhere in evidence upon the world's surface.

Some parts of the earth's crust are slowly sinking; a portion of the east coast of the State of New Jersey is said to be dropping. In other places the land is rising; it is claimed that the coast ranges in California are young mountains pushing their way through the coastal plain. Many such statements for different parts of the surface of the globe may be cited. These are effects of the so-called mountain-making or tectonic forces which act through long periods of time and over wide areas.

Some parts of the earth's surface are more settled or stable than others, and we do not expect severe crustal movements in such regions. New York City, resting on strong elastic rocks, is probably an example. The Adirondacks and vicinity, whose foundation is of the earliest geologic age, is never associated with earthquakes. In other places, crustal movements, that is earthquake phenomena, are from time to time to be expected. Japan and the Pacific Coast of America are such countries. As the earth's crust gradually changes, lines of weakness no doubt will be shifted from one part to another of the globe's surface, and what are now termed "earthquake countries" may no longer be so in the next geologic age.

I must distinguish between the volcanic and tectonic earthquakes. In the present discussion it is not necessary to consider the volcanic type. Volcanic earthquakes are generally local and their effects of smaller extent. They are comparatively rare. The tectonic or mountain-making earthquakes are more frequent in occurrence; they may affect large surfaces on the globe, as in the present instance; they may be severe, or so slight that only the most delicate seismic instruments will detect them. For a year previous to our great April earthquake, shocks were recorded by delicate instruments with great frequency in the neighborhood of San Francisco. While tectonic earthquakes are apt to occur more often in regions of proved crustal weakness and instability, they are nevertheless liable to occur anywhere and at any time.

The crust of California, dynamically speaking, is alive and active. Here the earth's surface is in growth and we are witnessing one instant perhaps in its development. Geologically speaking, the earth's crust in California is somewhat unsettled or unstable, and I see no object to be gained by not admitting this fact. Earthquakes are natural phenomena and should not be feared. We can not contend with nature's forces, but we certainly can try to adjust ourselves and our works most favorably to their requirements. Earthquakes offer to

the geologist most interesting dynamical problems, and their effects upon human construction, no matter how unfortunate, lend to the engineer and the artisan most valuable experience and counsel.

FAULT LINES IN CALIFORNIA

More than a generation ago geologists mapped out long continuous fault lines upon the face of California. These lines are the results of former slippings or accumulations of slips that have occurred in the past, often the remote geological past, and thorough study reveals their relation to California topography. Most of these important fault lines, if not all, run in a general north-northwesterly direction, essentially parallel to the mountain range lines, a parallelism which is quite natural and to be expected. A study of the report of Mr. G. K. Gilbert, Monograph 1, U. S. Geological Survey, describing the phenomena at Lake Bonneville, and the earthquake destruction in Inyo County, California, in 1872, also the work by Professor Andrew C. Lawson entitled "Sketch of the Geology of the San Francisco Peninsula," Fifteenth Annual Report, U. S. Geological Survey, page 405, will fully acquaint the reader with the geology of California and help him the better to appreciate what happened on the eighteenth of April, 1906.

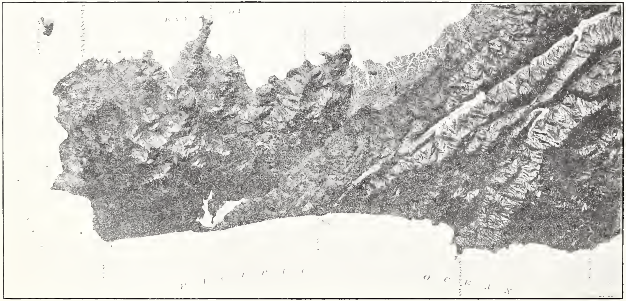

FIG. 1—*Relief Map of San Francisco Peninsula, by Professor Andrew C. Lawson; Consult Fifteenth Annual Report, U. S. Geological Survey, Page 405.*

The great earthquake of 1872 was accompanied by and was coincident with heavy slipping along parts of a pronounced fault line which traverses the western flank of the Sierras from Owens Lake in the south toward Lake Tahoe in the north. A relief map of the San Francisco peninsula given by Professor Lawson in the work above referred to, see Fig. 1., shows clearly a part of another great fault line which follows the coast and runs in the same general direction as the one in the Sierras. This great coast fault is clearly shown by the map, Fig. 1, to run through Lakes San Andreas and Crystal Springs of the Spring Valley Water Company. There are a number of lesser faults to be studied in the coast range region. These faults are lines of weakness in the crust along which movements and slippings have occurred in the past; and renewed ruptures or movements in the rocks far below the surface, at the same time that they produce earth vibrations, may also cause surface cracks and other evidences along these geological scarps,—effects which were so pronounced in 1872 in Inyo County, and this time in the coast ranges near San Francisco.

THE MAIN COAST RANGE FAULT

The earthquake of April eighteenth has affected the crust and the surface of the ground along the

main coast range fault. This fault or rift, Fig. 2, runs in an almost exact right line from Point Arena in the north, following along the coast through structural valleys or bays in a south-southeasterly direction, to Hollister in the south. Above Point Arena it disappears into the ocean, although there is some evidence that it curves to the east and approaches the land in the region of Cape Mendocino. This is probably the case; at any rate it would explain the considerable shock felt in Humboldt County. To the south of Hollister the fault may be traced by the observing eye along the western side of the San Joaquin Valley and into the desert lands to the south; some say almost to the head of the Gulf of California. As to the exact location and limit to the fault line in the south I can not speak definitely. I have not examined that region nor does the question of southerly extent really concern the engineer in this present earthquake problem. I have followed the rift from Point Arena to the region of Hollister and Tres Pinos. In this length of a little more than 200 miles the ground along the fault line was broken, and considerable horizontal and some vertical movement occurred throughout that distance. Movement and faulting below Hollister, if there was any, was slight, and I have heard of no authentic reports. Below Hollister, moreover, there is little improved

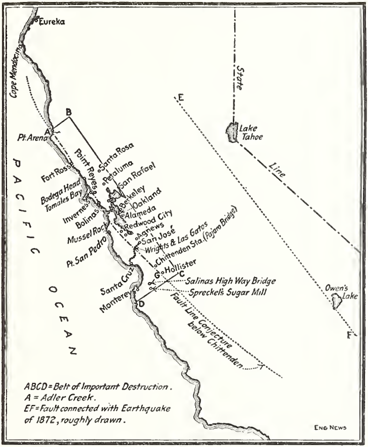

FIG. 2—*Map of California, Showing Position of Fault Line, Earthquake of 1906. Reprinted from "Engineering News," June 28, 1906.*

property and therefore hardly anything of engineering importance to destroy. Along the fault from Point Arena to Hollister the earthquake destruction was most severe. Water pipes, conduits, bridges, fences, roads, water courses, all things that crossed the line were crippled or rent asunder. In the north, trees were uprooted, broken and cracked, and everywhere along the fault buildings of weak construction were violently thrown down.

THE BELT OF MAIN EARTHQUAKE DISTURBANCE

The belt of great disturbance may be said to extend somewhat to the north of Point Arena into Humboldt County, and perhaps somewhat to the south of Hollister and Mt. Pinos, a distance of 300 miles or more. The disturbance was keenly felt for considerable distance to the east and west of the fault line, and a width of fifty miles may be assigned to the belt of great destruction. Within this belt will be found all the important examples of earthquake destruction to engineering works. It is plain that the extent of the seisma is large.

EFFECT OF TOPOGRAPHY AND GEOLOGICAL STRUCTURE

Within this belt, as I have already stated, the most severe racking of structures occurred right on the fault line, the most striking examples being the Pilarcitos conduit and San Andreas dam of the

Spring Valley Water Company of San Francisco, and the Pájaro River bridge on the Southern Pacific Railroad near Chittenden Station, where the railroad crosses the Pájaro River. These structures, though well designed, were much racked or even ruined, as in the case of the Pilarcitos conduit, because of the large and unequal movements of the ground along the rift. The intensity of shock, however, is observed to have varied greatly, and well-built structures which rested on hard and rocky surfaces were relatively little damaged. Rocks and the structures resting upon them were shaken by an elastic vibration without differential movement, and whenever the construction was intelligent and honest it withstood the shock. There are many examples of buildings of such behavior on rocky summits in San Francisco. Comparatively little destruction was meted out in cities like Santa Cruz, San Rafael and Berkeley, which rest on rocky foundation, or other sound coherent materials.

Within the belt of great destruction are found many localities or spots where considerable differential surface movement occurred, though at considerable distances to either the east or the west side of the rift. Examination shows such localities to be overlaid with loose incoherent material. In one place we find a loose river deposit,

in another a marsh, and in a third an artificial fill. Examples of destruction in such localities are found (1), near Salinas, where the Spreckels Sugar Mill, a first-class steel cage constructed building, was much racked; (2), in the San Bruno marsh, near South San Francisco, where the Crystal Springs conduit of the Spring Valley Water Company was smashed; and (3), on the filled ground areas of San Francisco in the Mission District and along the water front near the Ferry house, where the street surfaces were deformed into billow-like waves, and structures with weak foundations were generally destroyed. In all these cases the differential motions were of a secondary nature and not directly connected with the movements along the fault line. The vibration of the earth's crust caused marshes which were near to the center of the disturbance to shake like bowls of jelly, and loose sandy and alluvial deposits and artificial dumps and fills were much shifted and shaken about upon the firmer ground beneath them.

A line of considerable but lesser intensity of shock may be traced approximately parallel to the fault line through the bottom lands of the valleys which contain Santa Rosa and Healdsburg in the north, and Agnews and San José in the south, with the Bay of San Francisco as a central feature.

These bottom lands are alluvial deposits of soft and considerably incoherent materials. Structures resting upon these bottom lands were severely shaken, though in general there was little if any differential movement of the ground in such cities as Santa Rosa and San José. Structures located nearer the foothills of these same valleys, resting on firmer ground, were observed to suffer very much less.

Within the confines of the city of San Francisco one finds evidence of great variation in shock closely related to and to be explained by the nature of the surface topography. It is a general observation that the earthquake waves transmitted by the softer and less coherent materials and formations appeared to be much more destructive than waves which traversed the hard and more elastic rocks and other sound deposits. The billow-like effects that appeared in the streets of San Francisco near the Ferry house are most excellent examples of deformations in soft, incoherent materials. The sliding and rolling effects observed on some of the sand dunes and especially along the hillside at the northern end of Van Ness Avenue may be cited as allied phenomena. The great contortion of sandy deposits on the south bank of the Salinas River in the vicinity of Salinas and Spreckels is another good example.

POSSIBILITY OF FUTURE EARTHQUAKES NEAR SAN FRANCISCO

I believe that the crust of the earth acts like a more or less brittle skin on the surface of a plastic globe. I believe the interior of the globe to be potentially plastic despite its relatively high density, because of the great pressure to which the material is subjected due to the enormous loads of superincumbent materials. The crust can not be self-supporting like a spherical shell nor locally as a segment of a spherical dome because of the large radius of curvature of the earth's surface and small depth of shell or arched ring. For the earth's crust to act as a self-supporting stable arch or dome would demand the existence of arch ring or dome stresses in the crustal rocks far in excess of the crushing strength of granite. Wherever the pressure from within against the crust is relieved, the crust must sink, and where for some reason the interior increases its pressure against the crust the land must rise. The earth's crust may be conceived to rest like a brittle slab upon an interior of a semi-plastic nature; whenever the conditions of pressure between the crust and the interior become disturbed, the crust must give and adjust itself to put the stresses in the rocks into equilibrium. To produce this equilibrium the crust must give at its weakest

point. In this way a crack or slit, or as it is termed in geology, a fault, is produced. Within the confines of California one finds a region of structural weakness, and as has already been pointed out, the State is marked by a number of long fault lines running along the foothills of the high mountain ranges in the Sierra region and along the structural valleys of the coast ranges. Slippings and adjustments of the crust have occurred along these fault lines many times in the remote past, and the present evidences of geological faults and rifts are the accumulations of many past earthquake breaks. When a slipping has once occurred along one of these pronounced lines of weakness, either due to an actual rupture of the rocks or to the sundering of an old break, it is fair to presume that the crust in that vicinity has been set at equilibrium. It is also to be expected that a number of very minor shocks should follow in quick succession after a heavy earthquake. They represent secondary slippings and local readjustments after the main movement. A long period of time must then elapse before a sufficient accumulation of stress can result in the same region to produce another rupture and renewal of movement by overcoming the friction and partial cohesion of an old break. It is probable therefore that a heavy earthquake in the region of the main coast range fault will not occur in the

immediate future, and that the crust in the region of San Francisco has been put into equilibrium for a considerable period of time. I believe it probable that Western California will not be subject to a heavy earthquake for at least a century, but earthquakes can not be predicted and another one might come tomorrow. A shock of considerable severity might occur at any time, and it is plain that thinking men must be ready to expect surface disturbances somewhere in California in the next generation.

It is our duty to anticipate these disturbances. Any one who has carefully studied earthquake destruction can not fail to appreciate that great structural losses are due primarily, except in the immediate region of a fault line or upon loose deposits, to faulty design, poor workmanship, and bad materials; let us hope through ignorance and a blind disregard for earthquake possibilities; yet I regret to add that I feel convinced that much of the bad work is due to a combination of criminal carelessness, vicious and cheap construction. Rather than try to tell outsiders that San Francisco was visited by a conflagration I believe that it will do San Francisco and California in general more lasting good to admit that there was an earthquake, and that with honest and intelligent construction and the avoidance of geologically

weak locations for important structures, our losses within the earthquake belt would not have been so great.

DESTRUCTIVE PATH OF THE FAULT LINE

Referring again to Fig. 2, we note that the rift disappears in the ocean at the extreme north a few miles above Point Arena at the mouth of Adler Creek. From Adler Creek the fault may be followed southward approximately parallel to the coast line to Fort Ross, where it runs into the ocean about 2½ miles south of the fort. Earthquake vibrations were very severe in the neighborhood of Fort Ross, I believe more severe than in the vicinity of San Francisco, but there were no important human structures to demolish. Fig. 3 shows a redwood tree about six feet in diameter which happened to stand right on the fault line near Fort Ross. It was split into halves for a distance of 35 feet upward from the ground. The westerly half was sheared toward the north and actually moved past the east half a distance of about 8 inches. Fig. 4 shows a pine tree which was situated a few feet to the east of the fault line. It was thrown so that it leans toward the east. It was somewhat cracked at the base and its roots on the west side were torn, due to the shearing action along the fault line. The tree was subjected to torsion because it had roots on both

FIG. 3—*Redwood Tree, Situated on the Fault Line, near Fort Ross, Sonoma County, California.*

sides of the fault, which explains the cracking at the base of its trunk. Many trees were more or less ruptured along the fault where the line traverses timber growths; and in one place I observed leaning redwood trees for a con-

FIG. 4—*Pine Tree Standing on the Line of Fault near Fort Ross, Sonoma County; the Ruptured Surface Shows the Characteristic Appearance of Newly Plowed Ground.*

siderable distance distinctly marking the passage of the fault through a forest. Leaning trees make a very uncommon and inspiring sight in a redwood growth, where the trees are over 200 feet in height. At Fort Ross, near the fault, I noticed many partly decayed trees and trees weak in parts demolished and snapped off by the shock, when

sound ones close at hand were undisturbed. I could not help thinking how Nature in this way pointed out her weak and her strong construction. In the cities that I have visited within the earthquake belt, from Santa Rosa to San José, one can pick out the black from the white sheep in buildings. Natural and human works behave alike. They are governed by the same mechanical principles.

The fault line is lost in the ocean for some miles south of Fort Ross. It is again noticed as one proceeds southward, where it crosses the sandy spit of Bodega Head, which extends into the ocean. At this point the surface effects are very indistinct and of little moment to the engineer.

Again, the fault line disappears in our southward journey, but it distinctly follows through the structural trough which forms Tomales Bay and appears on land again at the southerly end of that bay near Point Reyes and Olema. From Point Reyes to Bolinas Lagoon the fault line is extremely distinct and this region offers to the geologist and engineer equally interesting evidence. At Bolinas the fault disappears into the ocean outside of Golden Gate and does not appear on land again until we reach Mussel Rock on the San Francisco peninsula. Along the coast above Mussel Rock to Lake Merced great coastal disturbances were

produced, due to landslides on the steep banks caused by the nearness of the shore line to the fault. Heavy landslides along the coast occurred also to the south of Mussel Rock at San Pedro Point and Devil's Slide, where the preliminary grading for the Ocean Shore Road, which is to connect San Francisco and Santa Cruz, was entirely wrecked.

From Mussel Rock the fault proceeds southward along a chain of small lakes between the San Bruno marsh on the east and the coast ranges on the west. These lakes are numerous, and the observing eye at once notices a connection between them and the characteristic geological formation which marks the line of the fault. Small basins or ponds, some brackish, some even salt, are of frequent occurrence along the fault line from Fort Ross to Hollister. Continuing southward from Mussel Rock and the chain of small lakes, the fault runs through a long and narrow structural valley, passes along the east bank of San Andreas Lake, follows the valley below that lake, and coincides with the longer diameter of Crystal Springs reservoir.

It then continues southward somewhat to the west of Redwood City and Palo Alto (seven miles distant) and crosses the Narrow Gauge Railroad in the neighborhood of Wrights and Los Gatos. Here

mountain tunnels on the railroad have been made impassable by slides so that trains can not cross through the Santa Cruz Mountains from San José to Santa Cruz. Agnews and San José are twelve and thirteen miles respectively to the east of the rift.

The fault may then be clearly followed to the region of Chittenden Station on the Southern Pacific Railroad, where it crosses the Pájaro River about 1,500 feet south of the station and passes right through the Pájaro River Railroad bridge. The fault line then proceeds inward to San Juan Bautista, or farther, where it leaves the region of important structures.

DIFFERENTIAL HORIZONTAL DISPLACEMENT

From Point Arena to San Juan all evidence clearly indicates that the ground on the west of the fault moved north from seven to nine feet relatively to the ground on the east. Straight fences that crossed the rift were invariably sheared so that they are out of alignment or offset from six to fifteen feet. All things that crossed the fault (water pipes, houses, dams, and water courses) were sheared. It is clear to the observer that the ground on the west of the fault moved; that on the east did so too. Probably the material along the fault moved in opposite directions on the two sides, with

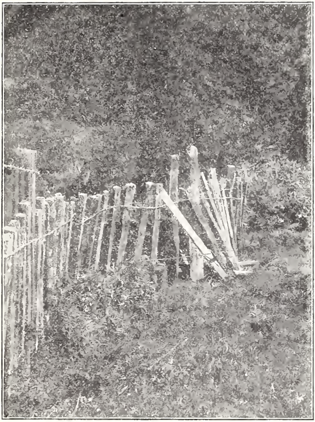

FIG. 5—*Fence near Fort Ross, Sonoma County, California, Offset Nine Feet at the Line of Fault.*

the resulting displacements mentioned. The tearing of the surface along the fault also clearly shows that there was some torsion in a clockwise direction when the eye looks downward. Fig. 5 shows a fence one-half mile south of Fort Ross which did not collapse, but was curved and bent to suit the lateral movements of the earth, so that its unmoved parts are now nine feet out of alignment. A second fence one-half mile farther south completely collapsed for a few feet on each side of the fault and was offset fifteen feet six inches. Near the head of San Andreas Lake a fence, Fig. 6, was offset seven feet. A roadway in the Point Reyes locality was dislocated about twenty feet. In all cases the west side moved north.

The amount of offset along the fault at the surface is affected by the nature of the surface material. On marshy and on sandy ground and on steep hill slopes and alluvial valley lands, the offset is sometimes more and sometimes less than the average, due to secondary motions of the looser surface materials or to local landslides on the steep hillsides. It would seem that there was somewhat more, perhaps two feet, sliding motion along the fault line at its northern end near Fort Ross than at its southerly end near Pájaro, where the movement diminishes.

DIFFERENTIAL VERTICAL DISPLACEMENT

The relative horizontal movements along the fault were much more marked than the differential

FIG. 6—*Fence neor the North End of Son Andreos Reservoir, Son Froncisco Peninsula, Offset Seven Feet ot the Line of Foult.*

vertical displacements, although the old scarps now somewhat rounded by the weather show considerable vertical differential motion for past times. In the north, in Sonoma County, due to the present

earthquake, one observes near Fort Ross a general lifting of the surface to the west of the fault line. The movement does not exceed four feet. In the south there is little, if any, differential vertical displacement.

ABSOLUTE MOVEMENT OF THE CRUST

Throughout the disturbed belt there is no doubt that the crust has been profoundly shaken. Latitudes and longitudes have doubtless been shifted a few feet, but it would be difficult to substantiate fully this statement. There is equally little evidence of change in elevation; yet mountain tops have probably been moved in elevation by small amounts. Only careful surveying and leveling and a comparison to geodetic records can throw light upon this question. The triangulation of the San Francisco Bay region is now being checked for this purpose by engineers of the United States Geodetic Survey.

SANTA ROSA

Santa Rosa, about fifty-two miles north of San Francisco on the California and Northwestern Railway, is nearly twenty miles east of the fault line. Nevertheless it was visited by great earthquake and fire destruction. Eastern people have heard little of the losses of Santa Rosa because they

were overshadowed by the largeness of the destruction at San Francisco; yet in my judgment, proportionately speaking, Santa Rosa's loss was greater than that of San Francisco. The city stands on alluvial ground. Its business center was wiped out by fire and practically every brick building in the business district collapsed in the earthquake. I believe all but two or three of Santa Rosa's brick buildings were razed with the ground by the temblor. But it is my judgment that the shock was less serious in the northern city than in San Francisco.

How then should the general destruction be explained? The brick buildings of Santa Rosa were carelessly constructed. Lime mortar was almost invariably used with bad brick bond. The sand of the lime mortar used was what is locally known as "drift" sand, containing, according to a local engineer, practically fifty per cent of loam. When we remember that it has been too common a custom in California to lay brick for small structures without sufficiently wetting them, in fact almost dry, what else should be expected, especially when we further observe a most inadequate anchoring of the floor and roof frames to the outer walls, and a usual absence of necessary cross walls or frames. Besides brick buildings are not capable of withstanding heavy earthquake vibration. It is a fault of design more than of workmanship. Upon this

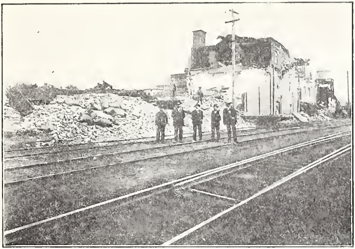

FIG. 7—*Santa Rosa Flour Mill. A Typical Brick Structure with Wooden Interior, Three Stories in Height; the Major Portion Completely Collapsed.*

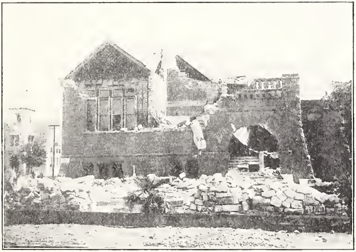

FIG. 8—*Carnegie Library, Santa Rosa. A Typical Brick Building with Wooden Interior Framing; the Outer Walls Faced with Cut Stone. Buildings of This Type of Construction Invariably Were Shattered near the Roof Lines. The Picture Is Representative of the Behavior of Stone-faced Buildings with Inadequate Wood Framing.*

point I will speak more in detail later in reference to brick structures in the city of San Francisco.

Wooden buildings in Santa Rosa with few exceptions were unaffected by the earthquake except for

FIG. 9—*A Scene in Santa Rosa Photographed Shortly after the Earthquake and Fire. The View Shows the Corner of Fourth and Mendocino Streets. The Ruins of the Court-House face Mendocino Street. On the Left in the Picture Is Seen the Collapsed Keegan-Brush Building, a Two-Story Brick and Stone Structure, Devoted to General Store Purposes. This Building Did Not Burn, and Ninety Per Cent of the Stock Was Saved. On the Right Side of Mendocino Street the Fire Destroyed Everything. In This Respect the Picture Is Instructive in That It Shows the Difference in the Destruction by Earthquake and Fire.*

the general throwing down of chimneys. The few frame houses which were wrecked collapsed because of rotten or faulty and improperly braced underpinning to the first floor or cellar. Frame

houses, well built, are adequate for earthquake countries.

No railway or highway bridges in the vicinity of Santa Rosa suffered. No breaks occurred in

FIG. 10—*The Collapsed Court-House Dome, Santa Rosa. The View Is Taken with the Camera on the Second-Story Roof; See Fig. 9. The Court-House Consisted of Three Stories of Brick, the Third Story Smaller in Plan Than the Other Two. The Third Story Supported the Wooden Dome.*

the water works system, its artesian sources of supply, or its pumps. A few house-service pipes broke at the house lines. No sewers were crippled. It is plain to me that there was little or no unequal resultant movement of the ground at Santa Rosa such as one finds at the fault line. The destruction was due merely to earth vibration and the brick

buildings almost without exception collapsed like so many sand piles.

The business portion of Santa Rosa burned because fires started simultaneously in the rubbish and the facilities for fighting fire were too limited to cope with a conflagration. There was never a lack of water, in fact there was more water than under normal conditions, because the people were not using their natural supply; and for the same reason the pressure in the mains was greater than under normal conditions, although some local Santa Rosans ascribed the higher pressure to the effect of the earthquake on the subterranean grounds surrounding the artesian wells.

Figures 7, 8, 9 and 10 show typical views of earthquake and fire destruction in Santa Rosa.

SAN FRANCISCO

To the student of structures San Francisco in the month following the earthquake offered a field of observation so large that I hardly know where to begin to describe my impressions. Within the city limits one found most varied examples of surface and foundation materials, from hard rock upon the hillsides to treacherous, filled ground along the water front of the bay and upon the old stream beds of the Mission Creek. Every degree of construction in building was presented,

from the first class steel cage constructed buildings, locally called "Class A," to the cheapest types of brick and frame houses. All grades of workmanship, good and bad; all types of design, scientific and unintelligent; all degrees of construction, from honest to dishonest examples, were to be seen on every hand. On adjoining lots one found the so-called fire-proof structure and miserable fire traps huddled together. Or one saw the ruins of a building carefully fire-proofed within, but entirely lacking in exterior protection to resist a conflagration from without. Many of the Class B structures were clothed with iron shutters and gave some evidence that the designer and builder had at least thought of exterior fire-proofing; but within, the building was ready to burn like the contents of a furnace.

Then as one walked through the desolate fire-stricken streets, one was constantly forced to compare the ruins of municipal and private buildings. Government buildings in general were well built, and it is not intended that they should be included in this criticism. There evidently was a difference in the construction of city buildings and those erected by private parties. Certainly there was a difference in their earthquake and fire resisting powers. School buildings and churches too, too often exhibited pronounced weakness in construc-

tion. I believe these statements do not apply to San Francisco only. The attitude toward careless construction for buildings of community interest is entirely too prevalent throughout the United States. The facts have not been brought home in other large cities simply because those cities have not been so sorely tested as San Francisco was in April, 1906. It is perhaps right to say in this connection that it is unnecessary to consider the personal integrity of builders, or to insinuate criticism concerning the ability of the architect. What should be emphasized first and foremost is a general principle applicable to cities and communities all over the United States, namely,—that the public in the building of municipal structures, school houses and churches, expects far too much for the money appropriated. The result therefore is a building of improper construction, and we need not wonder that such buildings showed themselves seriously weak when tested by a severe earthquake, and helpless in a conflagration.

The discussion for San Francisco naturally divides into three main parts:—(1), earthquake effect upon structures; (2), fire-proofing of buildings, and fire-resisting qualities of materials; (3), a critical digest to determine the best materials to be used and the most favorable types of design to be employed to resist earthquake stresses and retard

the progress of fire. In this paper I will restrict my remarks almost entirely to the earthquake effects.

EARTHQUAKE EFFECTS IN SAN FRANCISCO

As pointed out earlier in this paper, the intensity of shock was not found to be constant over any given area, but was greatly affected by the nature of the ground surface. Structures resting on the rocky hill slopes of San Francisco suffered least. In the swales between the hills, upon comparatively firm ground deposited there slowly by natural processes, one found increased destruction. The shock was felt with still greater violence upon the sand dunes, while the worst destruction in the city was meted out on the artificially made lands near the water front and upon the old swamps. Roughly speaking, then, one may emphasize four varieties of ground:—(1), rocky hill slopes; (2), valleys between the spurs of the hills; (3), sand dunes; and (4), filled ground; upon which, in the order named, was found earthquake destruction of increasing severity.

But this classification can only be helpful for a preliminary and superficial discussion. Well-built structures on proper, deep foundations stood the shock on soft ground, while buildings of faulty design went to pieces on much more favorable locations. One may be easily led into error in judging

of the degree of shock by the amount of destruction. A complete knowledge of the type of structure, grade of workmanship, and properties of materials used, together with the geological considerations, is necessary to establish an intelligent conclusion.

FIG. 11—*Street Surface in Front of the Ferry Tower, Showing Undulations and Cracks in the Asphalt Pavement.*

STREET AND SURFACE DEFORMATIONS

Great distortion of the surface was best observed in the streets, and was found on the filled areas and in some places, on the sand dunes. The best localities for observation were:—(1), Market Street near the Ferry Building, Fig. 11; (2), the water front on both sides of the Ferry Building, Fig. 12; (3),

the corner of Howard and Spear Streets, where the J. A. Folger Company's building was saved from fire; (4), the corner of Mission and Seventh Streets, the location of the General Postoffice; (5), Van Ness Avenue at Eddy Street; (6), the north end of Van Ness Avenue and the streets on the hillside slope in that vicinity downward to the water front on the north; (7), Howard Street, between 17th and 18th Streets, Fig. 13; (8), Valencia Street, between 18th and 19th Streets, where the Valencia Hotel was wrecked with great loss of life, and the main water pipes were sheared; (9), Fourteenth Street, between Mission and Howard Streets; and, (10), the water front near the Potrero District. I might enlarge this list, but these are the typical examples. Examples 5 and 6 represent surface distortions on sand dunes. The rest are examples of filled ground deformations. Upon the filled ground the surface was very generally thrown into billow-like waves, a type of disturbance which was best seen near the Ferry house. Upon the sand dunes the surface was shifted by sliding motion so that cracks and fissures appeared upon the streets at right angles to the direction of sliding.

It was in these areas that the sewers and water pipes of the gridiron system were so generally crushed and broken. Even had the main conduits survived, water could not have reached the hy-

drants in the lower Mission District. The brick sewers were uniformly helpless to resist destruction in these regions and the cast iron water and gas pipes fared no better. I believe reinforced concrete sewers in these districts would have shown

FIG. 12—*Rupture of Car Tracks and Pavement on East Street, Corner of Pacific Street.*

much greater resisting qualities, but I am convinced that even such material could not withstand earthquake stresses on the dividing line between made and filled ground. At such points flexible joints might have helped the sewer and water pipes, but it is difficult to conceive of a practical means for procuring flexibility at any given

point in a brick or concrete sewer. Moreover, it would be requiring a power of prediction not resting in human beings to determine the proper locations for flexibility. Important water pipes wherever possible should avoid soft ground by going

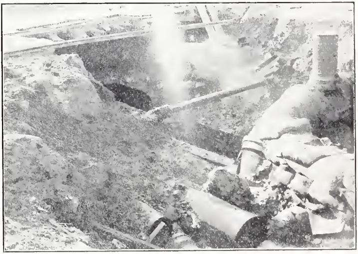

Fig. 13—*Scene Corner of Howard and Seventeenth Streets Showing Rupture of Car Tracks, Sewer, Water and Gas Pipes.*

around it, and those that must traverse filled areas should be of riveted steel or wrought iron with flexible joints at intervals. Greater probability of resistance to rupture might be further insured by encasing pipes traversing the most treacherous ground in tunnels of reinforced concrete with suitable clearance between the pipe and the tunnel

walls. An added advantage of this scheme would be ready means of inspection.

In discussing earthquake effects upon sewers and water pipes in the filled ground regions, one of necessity is led to consider fire problems as well

FIG. 14—*Collapsed Frame Houses on Howard Street, between 17th and 18th Streets. The One on the Left Is Completely Razed. At This Place the Earth Movements Were Especially Severe, and Even Good Construction Would Have Suffered.*

because the water supply and fire questions are so vitally related. Water mains should be generously provided with a system of cutoff valves commanding the direction of flow through the pipes of any given locality. At the time of the earthquake San Francisco was in dire need of a salt-water system, and immediate steps should be taken to provide

such a system and to secure a number of powerful fire boats.

ORDINARY FRAME HOUSES

Many frame buildings collapsed on the filled ground, Fig. 14; and an unreasonably large number on the more substantial areas of the city. Some of the destruction in the made land district was unavoidable, but much of the general collapse of frame houses was due to improper underpinning in the foundations. Such houses virtually stood on stilts; consult Figs. 15 and 16. Moreover, the cheaper frame buildings were provided with carelessly constructed brick chimneys built with weak lime mortar; naturally the brick work cracked to pieces. It is therefore easy to see why so many of these houses burst into flames immediately after the earthquake. It is said that fifty-seven fire alarms were sent to the Fire Department within the first half hour. Of course not all of these fires were produced by fallen or cracked chimneys in frame buildings. Some were similarly started in cheap brick structures, which are just as readily inflammable,—and still others by the breaking of electric wires of high tension, or through improper electric insulation of power wires.

Carefully built wooden-framed houses are especially well adapted to withstand earthquake

FIG. 15—*Frame House Wrecked in Santa Rosa; Due to Weak and Decayed Underpinning.*

FIG. 16—*Collapsed Frame House in San José Showing the Effect of a Lack of Transverse Framing and an Absence of Continuity in the Vertical Sticks at the Floor Levels.*

shock and represent a most desirable type for small dwellings. The weak feature is the brick chimney. But even this can be built so that cracking will not be so complete as to cause fire. For earthquake countries wooden buildings should be intelligently framed to act like an elastic cage or unit, and the foundations should be carried below the surface sufficiently to reach firm ground. It is too common a practice which completes one story of a framed house before starting the frame for the next story. Where there is no continuity in the main wall framing from floor to floor, weakness exists at the floor level; consult Fig. 16.

If brick chimneys must be used it is a mistake to use strong mortar above the roof line. With strong mortar a chimney top will fall in one piece and crash through the roof; with weak mortar it will disintegrate and the individual brick will roll off the roof.

ORDINARY BRICK BUILDINGS

The most general destruction by earthquake in San Francisco was observed in ordinary brick buildings. Brick walls were usually thin, of careless bond, and built with lime mortar of little strength. Apparently many brick walls were laid without wetting the brick before applying the mortar, because one found so many cases where the

crumpled piles of brick showed clean surfaces, the mortar not having adhered to the brick to any degree. These buildings were of timber framing within, and the floors and roofs were improperly anchored to the outer walls. The earthquake shook out whole sides of brick buildings because there was no provision for a proper tying or anchoring of the walls from within. The so-called "fire walls" above the main cornice were thrown down in almost every case. Had the earthquake occurred later in the day, the falling of brick from fire walls would have caused many deaths.

Where buildings of this class had trussed roofs of timber, the framing was generally imperfect. These roofs commonly rested on inclined rafters with no bottom cross tie to keep the rafters from spreading. The earthquake vibration tended to drop the peak of the roof and spread the ends, which, in kicking against the walls, forced them out and threw them down. In this way a number of brick school houses were severely shattered. Many brick buildings were built like weak boxes, with no adequate provision for transverse stiffness, because the structures entirely lacked transverse brick walls or frames. Brick structures in San Francisco and vicinity should never be built with lean lime mortar. One part of cement to four or five of lime mortar would give very much better results. At

least every other joist of the floor system ought to be carefully tied to the outer brick walls. The roof similarly should be anchored to the walls; and its main trusses should have properly designed lower chord tie rods, and not depend for their resistance to spreading upon the stiffness of the side walls of the building. Foundations of these structures should also be made with great care to have them act as units to prevent unequal settlement.

The prime requisite for a structure to withstand earthquake shock is elasticity; that is, the ability to return without serious damage to its original shape and position after being distorted. It should vibrate without offering great resistance to distortion; in other words, it should yield readily. The wooden framed and the steel framed building answer this requirement. To an almost equal extent the reinforced concrete building does so also. But structures of brick and stone built of blocks, like brick work and cut-stone masonry, with horizontal and vertical mortar joints do not answer the requirements of yielding and elasticity to any desirable degree. This is especially true when the interior framing is of wood and of the weak and faulty design depicted in the preceding paragraphs. Brick and stone walls when not sufficiently reinforced and intelligently strengthened and supported by steel framing are inadequate for import-

ant buildings in an earthquake country. Consult Fig. 17.

While I have been decidedly severe in condemning block-work construction I must admit that some brick structures made a good showing. They

FIG. 17—*A San José High School. Ordinary Brick Construction with Wooden Interior.*

are the exceptions that prove the rule. For every brick building that withstood the shock, it is easy to give a number of examples of complete failure. St. Patrick's Seminary, at Menlo Park, is an example of most excellent brick work, yet it was decidedly shattered in the main towers. It is not unreasonable to say that where brick structures withstood the shock they did so in spite of the fact

that they were built of blocks or because the shock was slight or the building favorably situated.

In San Francisco there were a number of large brick structures of most excellent type which weathered the earthquake with practically no

Fig. 18—*St. Francis Church, San Francisco; an Example of Excellent Brickwork.*

damage. I refer to several churches, see Fig. 18, to the Custom House or Appraiser's Building and to the Palace Hotel. The walls of the Appraiser's Building were thirty-six inches thick. The Palace Hotel was built immediately after the earthquake of 1868 and was intended to be earthquake-proof. The outer walls were most carefully designed, the window openings were crowned with arches and

the interior of the building was divided into compartments by numerous cross walls running parallel to both sides of the building. Looking down upon the ruins of the structure one saw a honeycomb of brick walls giving lateral stiffness in all

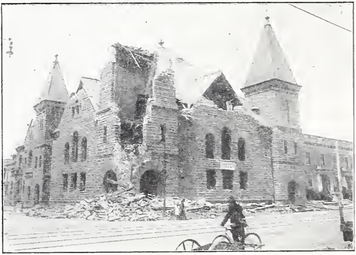

FIG. 19—*First Baptist Church, Oakland, California. The Dangerous Tower Was Pulled Down Several Days after the Earthquake.*

directions. Iron rods were embedded in the walls. The old Palace Hotel therefore should not be classed as a simple brick building, for it contained some attempt at reinforcement.

STONE STRUCTURES

Heavy stone structures, without steel frames, especially where the outer walls were not properly

tied to the interior floor and roof frames, suffered severely throughout the earthquake belt; see Fig. 8. Too many structures of this type for architectural reasons are made top heavy; see Fig. 19. Much of the recent construction at Stanford University may be criticized along these lines. In Oakland, Berkeley and San Francisco, heavy masonry church towers were invariably demolished, except where they were properly reinforced by interior steel frames or were strengthened by interior cross walls and tying rods. Heavy stone ornamentation should be discouraged and heavy stone cornices should be avoided. Where architectural effect is insisted upon, no expense should be spared in anchoring heavy stone cornices by the use of metal.

CHIMNEYS

Chimneys in San Francisco were built of brick and very often without cement in the mortar. With few exceptions the chimneys were thrown down by rupture within the middle third of the height. A number of lives were lost by falling power house chimneys; see Fig. 20. In the future I believe chimneys should be built of reinforced concrete and not of brick. Where brick is insisted upon, the bond should be carefully provided for, the mortar should be rich in cement and there should be some metal reinforcement.

CLASS B BUILDINGS

There is little to say regarding the earthquake effect upon the so-called "Class B" buildings. These

FIG. 20—*Fire Ruins of a Power-House of the San Francisco Gas and Electric Company, Station C. The Chimney of This Structure Fell During the Earthquake Shock, Demolished a Part of the Equipment and Killed One Person.*

structures consisted of self-supporting walls with an interior framing, partly of metal and partly of wood, with cast iron columns too often in evidence. For large structures of considerable height, one

certainly should not advocate self-supporting walls for earthquake countries. The Mills Building in San Francisco, Fig. 21, an otherwise excellent structure of ten stories, was designed with self-sup-

FIG. 21—*The Mills Building, San Francisco; Self-Supporting Brick Walls, Interior Framing of Steel, Floors and Partitions of Hollow Tile.*

porting walls and with main columns breaking joints at every floor level. After the earthquake the walls of this structure leaned from seven to nine inches into Bush Street. While the structure did not appear to be severely racked by the earthquake, the fact that the walls bore little relation to the interior frame, and the interior frame lacked continuity of columns at every floor, would not lead

me to recommend such a type of structure for an earthquake country. Moreover, the type exhibits great weakness in resisting fire because the walls tend to leave the frame. In Class B buildings it was a general observation to note heavy cracks run-

FIG. 22—*Fire Ruins of the Cowell Building, a Class B Structure, Showing the Great Destruction by Fire.*

ning diagonally in the outer walls. Such X-shaped cracks are also found in the brick work of steel-cage constructed buildings, but they obviously produce much more serious consequences in the Class B building, which has no steel frame upon which to depend for unity and coherence.

REINFORCED CONCRETE BUILDINGS

There were no reinforced concrete buildings in San Francisco because before the fire there had always been successful opposition to their introduction. In a few buildings reinforced floors and columns had been used, but there were no outer walls of reinforced concrete. Reinforced floors were common in Class A structures, where they shared favor with hollow tile floors. The little San Francisco evidence that one finds, considering also a few reinforced structures, or partially reinforced structures in other places, such as in Oakland and Palo Alto, leads one to the conclusion that buildings scientifically designed in reinforced concrete present admirable qualifications for earthquake resistance. There is no reason why reinforced concrete cage constructed buildings of at least six or eight stories in height should not be built in San Francisco. A reinforced concrete structure, when intelligently designed, generously proportioned and honestly built, is a monolith of great coherence and high elasticity, combining the very properties best able to resist earthquake vibration.

CLASS A BUILDINGS

Class A structures stood the earthquake shock admirably. Their steel frames were not materially impaired. These buildings vibrated like tuning

forks. It appears that the base of such a structure oscillated and moved with the earth, while the top tried to remain quiet. This statement is substantiated by the general evidence that less shock was felt in the upper stories of high buildings than in the floor levels near the street. Again it seems to be a fact that books and other loose objects were less disturbed and thrown down in offices in upper stories than in the those near the basement. The main steel columns of Class A buildings should be as continuous as possible from roof to cellar. Splices should be generously built, and it is always wise to run column pieces through several floors. These high structures were subjected to a considerable racking stress at floor levels, as is evidenced by the lines of rupture in brick walls at the floor horizons. In the future I believe that steel frames for Class A buildings should be provided with considerable knee-braced framing in the vertical planes between the main floor girders and columns to which they rivet; and wherever possible, diagonal framing should be introduced similar to that provided to resist wind stresses. Wind stresses very commonly are fictitious or imaginary, and certainly never approach the limits provided for; but earthquake stresses, while they fortunately do not occur very often, are intense and of the nature of impact forces. The engineers upon whom may devolve the

design of Class A skeletons in the immediate future should insist upon their structural requirements with greater determination than in the past, and not allow the architect to injure the strength of the building for the purpose of securing some less necessary architectural feature or embellishment.

Earthquake forces, relatively speaking, are unlimited in amount when the strength of human structures is under consideration. The amount of earthquake stress produced in a member of a structural steel frame is directly proportional to the resistance offered. The stiffer a structure, the greater will be the induced stress produced by earthquake vibrations. The more a structure is capable of yielding, like a willow tree to the storm, the less will be the tendency for earthquake rupture or collapse.

A committee of the American Society of Civil Engineers in its report on buildings states: "Sufficient evidence is at hand to warrant the statement that a building designed with a proper system of bracing to withstand wind at a pressure of thirty pounds per square foot will resist safely the stresses caused by a shock of an intensity equal to that of the recent earthquake." For bridges and towers, engineers usually provide diagonal members to resist wind stresses. They would use diagonal framing in high buildings also, except for the objection

of the architect. It is my judgment that diagonal framing is not desirable for high buildings in earthquake countries. Such framing consists of triangular parts. Geometry teaches us that a triangle can not change its shape without changing the lengths of its sides. Triangular framing therefore is stiff and unyielding and calls forth earthquake stress to the full capacity of the diagonal wind members. If a stiff frame of triangles is subject to earthquake vibration of severity, rupture at the weakest places is extremely likely. The effect of the earthquake on the Ferry tower in San Francisco justifies the above statement. In this tower diagonal wind bracing was used. In the fifth and sixth floors of the towers the diagonal rods were either buckled or ruptured or broken at the eye-ends. In some cases the rivets connecting the gusset plates and angles sheared off, the stress finding in each case the weakest point. The stresses exceeded the equivalent of a thirty-pound wind pressure many times. This is proven by the permanent set or elongation of the diagonal rods. In five cases, including three two-inch square rods, it was necessary to cut off the screw ends to take up the slack. The total stretch in some cases amounted to more than three inches.

For earthquake conditions triangular framing for high buildings is not so desirable as a rect-

angular framing with stiff joints and continuous members. In steel buildings, rectangular framing is best produced by substantial continuity in the main columns and by bracing these columns with deep horizontal spandrel girders; or by more shallow spandrel and floor girders strengthened with heavy knee braces.

Unlike the triangle, the rectangle can change its form without changing the lengths of its sides. With spandrel girder and knee bracing, therefore, the main columns by their elasticity and continuity can yield and vibrate to a considerable extent without endangering the integrity of the building's frame.

I therefore conclude that the best type of framing in a steel skyscraper consists in the generous use of deep spandrel girders, preferably of the latticed truss type. The new Humboldt Savings Bank on Market Street is an excellent example. The old Call Building has an excellent lateral framing.

In the basement of the Flood Building, on the south side, a number of rivet heads were sheared off in the connections between the girder beams and column shelf angles upon which the beams rested. These ruptures were undoubtedly produced by racking motion coincident with the earthquake vibration. Racking stress in buildings

certainly had its greatest destructive tendency in the first floor above the ground.

Earthquake vibration in high buildings puts a considerable stress upon the floor connections and columns, but does not tend to produce much destructive effect in the floors; on the other hand, it is clear to see that it does produce a very considerable shearing stress upon partitions, tending to destroy and crack them. This observation leads me to state that I do not advocate hollow tile partitions for high buildings in earthquake localities. Reinforced concrete partitions are much more suitable. Double metal lath and plaster partitions also have merit. I have no particular grievance against hollow tile construction, but partition tile is not a good earthquake material. It is essentially brittle, and difficult to build into a coherent mass. It can not stand flexure or distortion of any kind. For similar reasons I believe there is decidedly more merit in reinforced concrete floors than in hollow tile floors.

The earthquake vibration very generally produced X or so-called "earthquake cracks" in the outer curtain walls of Class A structures. It was very common to see brick work shattered between windows; and on large side walls, without window spaces, examination showed cracks running at angles of 45° to the horizon. Often heavy crack-

ing was observed at a corner of a building, see Fig. 23. Such destruction is not so serious in Class A buildings as in those designated Class B,

Fig. 23—*The Monadnock Building, Showing Heavy Diagonal Cracks in the Brick Curtain Walls along the Northeast Corner for the Full Height of the Structure.*

which have self-supporting walls, because it is a simple matter to restore the wall at any floor level of a Class A structure without disturbing the rest of the building. Much of the heavy cracking found

in Class A buildings may, however, be attributed to improper bond or anchoring in brick work, and to mortar too lean in cement. To me a building with a properly designed steel skeleton and light walls of reinforced concrete, supported by the main frame at each floor level, represents a type containing very much more merit to withstand earthquake shock than structures with brick and terra cotta curtain walls. Such reinforced concrete curtain walls can be made lighter than brick and terra cotta walls, thus reducing the dead weight of the structure. Brick, stone, and terra cotta curtain walls can be safely used, however, especially when carefully anchored to the structural frame.

Exposed side walls of a number of Class A buildings had face brick finish on ordinary brick curtain walls to give a dressed appearance. In most of these cases the face brick were tied to the backing by no other means than what is commonly called the clipped course bond. The racking of the earthquake threw out large areas of such face brick. The best example that came to my notice was found on the west wall of the Merchants' Exchange Building. The clipped course bond for facing brick should be prohibited.

I have already stated that in high buildings the earthquake racking was most severe near the street level. One found in nearly every Class A building

prominent cracks in the first story walls (Fig. 24), especially at points where heavy weights were concentrated upon corner columns. The stone work of corner columns was severely cracked where the masonry rested upon concrete under the sidewalk,

FIG. 24—*Flood Building, Northwest Corner, Showing Heavy Earthquake Cracking of the Sandstone Masonry Enveloping the Steel Corner Column.*

but hardly at all where the stone masonry was carried by the steel frame. Main columns acted like stilts to support the superstructure above the ceiling of the street floor, and prevented the collapse of many a building by column rigidity and continuity at the floor connections in the level of the second floor. It is plain that such floor connections

can not be too carefully designed. The most pronounced cracks at first-story columns were found in the Flood Building. One saw them also to good advantage on the sandstone front of the St. Francis Hotel (Fig. 25). Cracking of this character is not an evidence of weakness in the body of the building.

In Class A structures terra cotta was very generously and profusely used for ornamentation on the facing of the curtain walls of the street fronts. Being a material of the same nature as hollow tile, it is brittle and lacks toughness. It was generously spalled by earthquake vibration, and, while I by no means wish to imply that its use should be prohibited, I think it should be very carefully selected, be well burned, be used with greater thickness than in the past, and the hollows in the blocks should be filled. Highly ornamented terra cotta should be discouraged. The earthquake produced considerable spalling in the terra cotta of the Mills Building, and very generally damaged the terra cotta face of the Fairmont Hotel, especially on the north front (Fig. 26).

The foundations of high Class A buildings with small bases can not be designed with too great care. Where such structures rest on sand or near the filled ground areas, the foundations should be deep. Deep pile foundations have given excellent results, even on the filled ground. It is a general

FIG. 25—*St. Francis Hotel, Southeast Corner, Showing Heavy Earthquake Cracks in the First Story of the Sandstone Front.*

observation that structures resting on pile foundations in the made ground were much less affected than adjoining buildings on shallow foundations. The cable roadway on Market Street, where it approaches the Ferry Building, was founded on

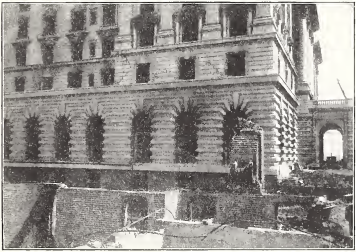

Fig. 26—*Fairmont Hotel; North Front, Showing Earthquake Cracks in the Terra-Cotta Veneer of the Second Story Walls.*

piles, and it sank little when compared to the general dropping of the street surface along the sides of the tracks. Other types of foundations, such as that under the Call Building, which is of the solid slab variety, have given equally good results.

Intelligently built foundations, not only for buildings but for all kinds of structures, were un-

affected by the earthquake. Well-built foundations are adequate. Depth is a prime consideration.

Important structures should not be built on treacherous ground. The site of the general Post-office (Fig. 27) was very unhappily chosen. That

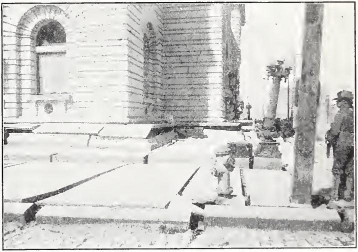

Fig. 27—*General Postoffice, Southwest Corner, Showing Severe Distortion and Subsidence of the Sidewalk and Street Levels.*

building, while exceedingly well built, rests on filled ground, and under its southwest end ran an arm of the Mission Creek. In this vicinity the ground was very much disturbed, and the street fell away from the building. The structure, while it stood and was saved from fire, was severely racked, and its beautiful granite fronts were badly

cracked on all sides. The interior partitions of the building were of double hollow tile, and were greatly destroyed. The structure represents an example of a building with heavy masonry walls with a partial and too light a steel frame. Con-

FIG. 28—*Earthquake Cracks on Sandstone Piers of the Ferry Building. These Piers Enclose Steel Columns with a Complete Air Space between the Steel Columns and the Stone Blocks. This Explains the Large Amount of Cracking and Shows That the Stone Piers Are Not Required for the Support of the Second Story.*

sidering the material upon which it rests, the building withstood the earthquake surprisingly well.

The Ferry house exhibited another example of excellent construction in a treacherous location. Due to the movements of the filled ground, there was no doubt a considerable pressure brought to

bear against the structure from the land side, tending to thrust it into the bay. The building rests on piles in large clusters, and withstood its severe test admirably. The top of the south end wall fell out. The stone work near the street level on the main pilasters was badly cracked (Fig. 28). In the second story horizontal joints were opened throughout the west front length of the building. The marble plates on the interior walls were much broken. The tower was shaken like a tree or flagpole in a vertical plane east and west, nearly coincident with Market Street's length. The east and west faces of the tower were therefore badly racked, just above the roof of the main building, and the stone facing at these places was thrown down, causing considerable destruction in the interior in the central portion of the building below the tower, see Fig. 29. The upper portion of the tower was originally designed in stone, but the consulting engineers advised the substitution of metal sheeting to reduce the weight, and this fortunately was done. Had the upper portion of the tower been of stone, I believe the destruction would have been very much more serious. The stone facing of the tower was backed with brick, and this masonry was supported by a steel frame, as in Class A buildings. It appears that the steel frame was built too light, especially the diagonal members. These

diagonals should have been heavier, and of stiff sections instead of rods. Some of the diagonal rods were snapped and some gusset plate connec-

Fig. 29—*The Ferry Tower Shortly after the Earthquake.*

tions and riveted joints were ruptured. I have already referred to the superior merit of quadrilateral framing, using spandrel girders and knee bracing. The tower was rapidly dismantled, the

steel frame strengthened and repaired and reclothed with reinforced concrete curtain walls.

THE FIRE DAMAGE IN SAN FRANCISCO

The lessons to be learned from the San Francisco conflagration are many, though not new. A discussion of this subject will in the main repeat the results of the studies of the Baltimore fire. Nevertheless, the question of fireproofing in San Francisco should and will receive the closest attention. It is a very large and important subject and of sufficient dignity to warrant a description by itself. Being without the purpose of this paper, it is not here treated. I will only add that such a discussion should pay some attention also to the fire calamities in Santa Rosa.

EARTHQUAKE DESTRUCTION TO THE SAN FRANCISCO WATER WORKS

The important destruction to the works of the Spring Valley Water Company occurred between San Mateo and the city of San Francisco. There was practically no damage to the water sources and works in Alameda County.

The Alameda conduit between the source and Burlingame lies in a region of lesser disturbance, and appears to have been subject to about the same degree of shock as the Contra Costa Company's works, which supply water to Alameda, Oakland

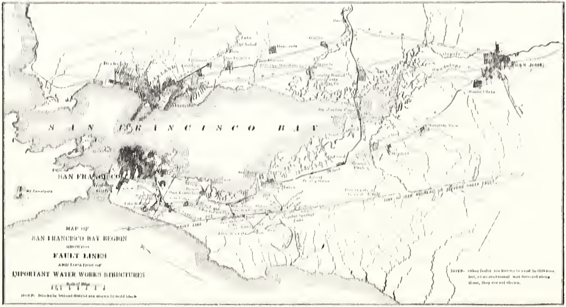

FIG. 30. *Taken from the Report of the Committee on the Effect of the Earthquake on Water-Works Structures, American Society of Civil Engineers, Proceedings, Vol. XXXIII, March, 1907.*

and Berkeley. It is significant to observe that there seems to have been little or no damage to the submerged part of the Alameda conduit where it runs under and across the southern end of San Francisco Bay.

The map, Fig. 30, clearly shows the water works property of the San Francisco Bay cities within the region of considerable earthquake disturbance. This map is taken from the Earthquake Reports of San Francisco members of the American Society of Civil Engineers; consult the Proceedings of that Society for March, 1907.

The Pilarcitos reservoir is to the west of the main fault line, and is separated therefrom by a range of hills known as the Sawyer Ridge. That reservoir is thoroughly intact, and its 95-foot earth dam is unaffected. The waste-way conduit connecting it with San Andreas Lake is also intact.

The main fault line runs through Crystal Springs Lake, but in no way appears to have affected the imperviousness of its bottom. The older Crystal Springs dam, which separates that lake into halves is crossed by the fault. Evidence on the roadway and roadway fences over the dam shows that the dam was sheared about five or six feet in the manner already explained under the heading "Horizontal Differential Motions Along the Fault." This dam, like the San Andreas dam, aside from trans-

verse cracks parallel to the fault line, also exhibits a number of longitudinal cracks along the roadway. When the huge concrete dam was built at Crystal Springs, the older dam became submerged, and to produce the roadway a fill was placed upon the dam of less coherence than that of the material of the original dam. It is impossible to determine whether the imperviousness of this dam below its upper and newer portion has been affected by the shearing action because the water is at the same level on the two sides. From the behavior of the San Andreas dam, however, I am led to believe that the shearing, even of five feet, has not been sufficient to cause serious perviousness, and should the water be released from one side of the dam, I believe it would be retained on the other. If my argument is valid I believe it indicates one advantage of a properly constructed earth dam with a clay core over a light dam of masonry and especially a light arched masonry dam of bold design like the Bear Valley, in Southern California.

The huge concrete dam at Crystal Springs, 115 feet in height above the natural surface, is parallel in length to the fault line. Its curvature is slight compared to the dimensions of its cross section. Arch action is negligible. The dam should be considered as a straight gravity dam. It was probably subjected to a series of thrusts and pulls in vertical

planes along its length since it parallels the fault. Its inner face has a much heavier batter than the Rankine or Wegmann calculations would require. The engineer of the dam, Mr. Hermann Schussler, states that he made the batter of the inner face one in four because of earthquake possibilities, he having experienced the earthquake of 1868. This dam is practically unaffected by the earthquake. Some who have examined it state that they have found slight cracks near the base of the downstream toe, but I did not see them, and they certainly are not serious. The intake works at this dam, the Crystal Springs Pumping Station, and all accessory construction in the neighborhood were left practically intact by the earthquake.

The fault touches the eastern edge of San Andreas dam, an excellent construction of earth and clay, 93 feet in height above the original surface of the ground. The fault line is nearly at right angles to the dam. As an eye witness I am convinced that this dam was subjected to a most severe earthquake shock, and since it retains the waters of San Andreas Lake, just as well as before the earthquake, it should be a source of great satisfaction to its designer and builder. Skilfully designed and well built earth dams have been proven by our great earthquake to be structures of great stability, deserving of increased confidence.

At the San Andreas dam the ground on the eastern bank was considerably scarred by cracks running northwest, where the fault line crosses the nose of a hill which naturally projects to form the dam's abutment. There must have been some motion at this point, possibly five or six feet, but it is not clear on the surface. The cracks which were pronounced in this nose or abutment were in the abutment and not in the dam itself. There were a number of smaller cracks running in the same direction at the extreme westerly end of the dam. On the dam's roadway there were small longitudinal cracks to be observed throughout its length, apparently due to the unequal settling of the triangular masses with respect to the core, but they were not serious. I am convinced that an earth dam properly constructed will stand a violent shock. Wherever possible a dam should not cross a geological fault at right angles.

The wooden flume starting near the Crystal Springs Pumping Station, which enters the San Andreas reservoir near the east end of its earth dam, completely collapsed just below that dam where the main fault line crosses the flume. At this place the flume was supported on a wooden trestle about fifty feet in height. In the same locality a waste-way conduit built by day labor, of selected brick with cement mortar, provided a dis-

charge from San Andreas Lake into the valley below the dam to discharge water into Crystal Springs reservoir. The gate-house for this conduit is near the eastern end of San Andreas dam, about 300 feet from the fault line. It is built of selected brick with cement mortar, and exhibits no cracks whatever. About 1,000 feet below the dam the brick conduit curves to the west to its discharge point, and in so doing crosses the fault line. At this crossing the conduit was sheared completely, but due to the excellence of the mortar, the brick was sheared more readily than the cementing material of the joints. This speaks volumes when we reflect upon the general destruction of brick structures throughout the earthquake belt.

The Crystal Springs conduit was not damaged between Crystal Springs dam and San Mateo, but between that city and San Francisco it was ruptured in a number of places where it crosses the marshes. It is mainly a 44-inch laminated wrought iron pipe, $\frac{1}{4}$ inch in thickness, with riveted joints and rivets $\frac{1}{2}$ inch in diameter. The worst destruction occurred in a distance of about 1,600 feet where the pipe crosses a salt marsh between San Bruno and South San Francisco. Here the pipe rested upon a wooden floor supported by pile bents. These piles on the average penetrated the mud to a depth of about 40 feet. The salt marsh evidently

shook like a bowl of jelly, the vibration being mainly in a south-southeasterly direction or nearly at right angles to the length of the trestle. It appears that during the vibrations of the earthquake

FIG. 31—*Rupture of the 44-inch Crystal Springs Conduit on the San Bruna Marsh; Picture Taken May 2, 1906. The Wooden Supports under the Pipe Are Temporary Forms Built after the Catastrophe. The Pipe Has Been Straightened Preparatary to Repairing the Transverse Riveted Joints.*

the trestle moved with mother earth. The pipe, due to its inertia, tended to remain quiet. As a result the pipe was alternately thrown from one side to the other of the trestle floor and its wooden box covering was generally smashed. The pipe broke at transverse circular riveted joints, sometimes by tension, and sometimes by crushing. Fig. 31

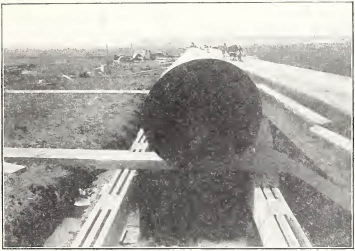

Fig. 32—*Rupture on Crystal Springs Pipe Line, San Bruno Marsh.*

Fig. 33—*Crystal Springs Conduit between San Mateo and Millbrae. Temporary Cut-Off to Stop the Flow of Water toward San Francisco and Yet Maintain a Pressure and Supply for the City of San Mateo.*

exhibits a view of one of the ruptures on the San Bruno marsh. Figs. 32 and 33 show other scenes along this pipe line during the period of repair immediately following the earthquake. Redwood planks were used for the temporary sills and stringers because larger timber was not quickly available.

The Pilarcitos conduit for a considerable distance practically coincides with the main fault line. Indeed, one might almost imagine that the break in the ground was purposely staked out along the pipe line, or vice versa, from a point somewhat below San Andreas dam to Frawley gulch, a distance of six miles. In this length the conduit is 30-inch laminated wrought iron pipe, about 3-16 inch in diameter. The center line of the pipe is usually found about three or four feet beneath the ground. In these six miles of length the pipe was ruptured in a great many places, at one place by tension and at another by compression. The direction in which the pipe line crosses the fault determined whether the pipe was torn apart or telescoped. Nineteen ruptures were observed by me from a point near the northern end of San Andreas Lake to Frawley gulch, a distance of about three miles. All ruptures occurred at transverse riveted joints. There were some places where the pipe collapsed; in one instance, for a length of about fifty feet. There were no doubt many more ruptures in this length

but they had not been uncovered. At tensile breaks the pipe was pulled apart by amounts varying from almost nothing to as much as five or six feet. At

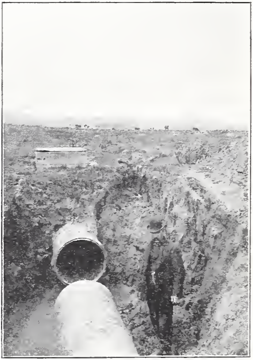

Fig. 34—*Rupture on Pilarcitos Pipe Line near North End of San Andreas Reservoir.*

compensating places the pipe was telescoped by similar amounts. Fig. 34 shows a break in this pipe line near the up-stream end of San Andreas Lake. The pipe at this point was pulled apart 53½ inches. A property fence, Fig. 6, which crossed

the pipe line about ten feet to the south of this rupture, was offset seven feet along the fault line, the two parts of the fence remaining straight and parallel to their original direction. At Frawley gulch the conduit crossed a timber trestle heavily built,

Fig. 33—Collapsed Trestle at Frawley Gulch, Pilarcitos Pipe Line Spring Valley Water Company.

about 100 feet in length and some 25 feet in maximum height. Some of the timbers of this trestle were partly decayed, but the structure certainly was not weak. This trestle was about ½ mile to the east of the fault line. Nevertheless the shock was so severe that it entirely demolished the trestle and pipe which it carried. The trestle probably vibrated in a vertical plane normal to its length.

and was thrown down-stream to the southeast, as shown in Fig. 35.

From Crystal Springs reservoir to Lake Merced the surface of the ground usually is what is known as black adobe land. In places it is yellow adobe

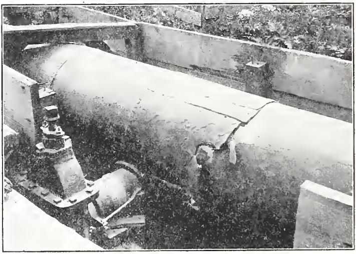

FIG. 36—*Telescoped Rupture, Pilarcitos Pipe Line, Spring Valley Water Company.*

and sometimes it is a mixture of the two. The series of ruptures in the Pilarcitos pipe line to Frawley gulch inclusive are therefore found upon firm ground unlike the material at the San Bruno marsh. The destruction was due to the proximity of the fault line or actual coincidence of the pipe line therewith, and as has been repeatedly shown by the evidence of this paper, construction no mat-

ter how good was unable to withstand the stresses along the fault.

I have not examined the Pilarcitos pipe line

FIG. 37—*Diagonal Ruptures, Pilarcitos Pipe Line, Spring Valley Water Company.*

beyond Frawley gulch to the city, but ruptures were probably not so numerous nor so serious in this length. The same remark applies to that portion of the Pilarcitos pipe line near Pilarcitos reservoir. The Pilarcitos conduit must be abandoned.

Figs. 36, 37, 38 and 39 show additional ruptures in the Pilarcitos pipe line between San Andreas Lake and Frawley gulch. In Fig. 36 the pipe line,

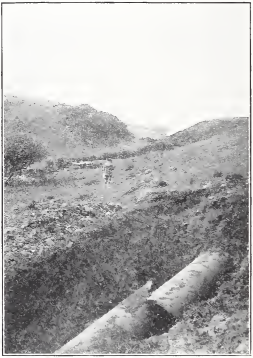

FIG. 38—*Diagonal Rupture, Pilarcitos Pipe Line, Spring Valley Water Company.*

supported on a timber framing, crosses a small swale. The pipe was telescoped 41 inches, and the blow-off valve connection was partly ripped from the conduit. Fig. 37 shows two ruptures a little

to the north of the break in Fig. 36. At the point where the man is standing the fault line crosses the pipe line at an angle of 45°. The pipe was sheared so that its parts are 20 inches out of alignment, and are moved toward each other 40 inches.

FIG. 39—*Collapse by Compression at a Small Trestle, Pilarcitos Pipe Line, Spring Valley Water Company.*

Fig. 38 is a closer view of the same rupture. Fig. 39 shows the pipe crossing a small gulch. The blow-off valve situated at this point was stripped from the pipe and thrown ten feet. The pipe was telescoped 49 inches and thrown out of alignment, as shown. This rupture strikingly shows that the pipe metal was of high quality.

The San Andreas pipe line lies between the Pilarcitos pipe and the Crystal Springs conduit; it is therefore not so near the fault line as the Pilarcitos pipe and avoids the marshes in the region of the Crystal Springs conduit. Its injuries were relatively slight. Only one important rupture came to my notice. It was quickly repaired by putting temporary banding on the pipe.

All the main conduits of the Spring Valley Water Company, with the exception of the San Andreas conduit, were considerably damaged, and in the fortnight following the earthquake no water reached the city from the Pilarcitos, the Crystal Springs, or the Alameda sources, although water from Pilarcitos might have found its way through the waste-way conduit to San Andreas Lake, and thence to the city through the San Andreas conduit after its repairs. San Andreas Lake temporarily became the distributing reservoir for the city and probably will so continue in the future.

It is plain that the water works of the city of San Francisco was subjected to a test more severe than the hand of man could devise. The water supply of a city is a most important matter, and ever since the earthquake the water problem has been the greatest one of many problems which have concerned the citizens of San Francisco. It is not surprising therefore that much concern was ex-

pressed about the water situation, and it is readily appreciated that the earthquake task of the Spring Valley Water Company was neither small from an engineering standpoint nor enviable from the municipal and political side. The destruction to the Spring Valley Water Company's plant as outlined above was produced by nothing less than a cataclysm, something which the mind of man could not foresee, and whose effects no engineering structure no matter how good could resist. The Crystal Springs conduit was of excellent design, but it was doomed on the marshes. The Pilarcitos pipe line had to succumb; it was right on the line of fault for a length of six miles. In the future it will be wise to avoid marshes and made ground for important pipe lines, and flexible joints should be introduced at intervals. The city was saved a terrible water famine simply because the San Andreas conduit, with slight repairs survived the general destruction. For safety the city needs a number of sources of water, in localities widely separated and not in the same geological region, with a number of main conduits so arranged that they will not tend to be destroyed all at the same time. The Spring Valley conduits have answered these requirements in so far as one of their number survived.

Buildings and other structures in San Francisco to a great extent have been notoriously poor. The

same is true in other cities in the earthquake belt. The time is ripe for the people to realize that they must enforce proper building laws and a proper attitude toward healthy construction both in municipal and in private works. The works of the Spring Valley Water Company are relatively of an exceptionally high type of construction. Its wrought iron conduits after thirty years of use, even in their present demolished condition, exhibit surprising preservation. Its pumping stations have survived where nearby structures collapsed. The Crystal Springs dam needs no praise. The earth dam at San Andreas fulfills its functions as well as ever, although it was directly on the line of the main fault and was greatly scarred. Faulty work and weak engineering construction may be found in other States of the Union, as well as in California. The engineer and contractor are not alone to blame, and I am not willing to criticize them. The community itself is partly responsible, because it expects and demands too much for its money.

I have already alluded to the destruction of water pipes within the city. Had the main conduits remained intact, there would still have been great difficulty in fighting the fire. Small reservoirs within the confines of the city should be connected with the main conduits by pipes of considerable size in no way connected with nor dependant upon the

gridiron system of the streets. Had the city reservoirs of San Francisco tapped the large conduits independently of the street mains, some of the delay in obtaining water and fire pressure in the first fortnight after the earthquake might have been eliminated. Within the city confines also there should be larger reservoirs than are now provided.

Within the city boundaries, main branch pipes, and in general the pipes of the gridiron system were much destroyed. In the softer and made ground this was especially true. Moreover, the great extent of the fire destruction left innumerable tap and service pipes to hundreds of burned buildings in a most dilapidated condition. Explosions of gas mains, Fig. 40, added further rupture to the streets and the pipes beneath them. With this general demoralization of the gridiron system within the city and the loss of the Pilarcitos and Crystal Springs conduits, the situation on the morning of the earthquake may be understood. There was little water in the city and no water pressure.

Earthquakes are not uncommon in California and they will naturally occur again. There has been much talk of tapping the water sources of the Sierra Nevada Mountains and bringing that water to San Francisco by conduits and water courses which must be nearly 200 miles in length. As already stated, it is to be desired that the city have a num-

ber of distinct sources of water, but in the light of our present catastrophe how much more danger must there be of earthquake destruction upon a line of so extended a length? Conduits in duplicate would be of no avail; when one breaks so will the

FIG. 40—*Gas Main Explosion, Valencia Street, near Market Street, San Francisco.*

other. The only safeguard will be two distinct conduits running in widely separated districts, but such a proposition would entail great cost.

PALO ALTO

Palo Alto is seven miles east of the fault line; its important earthquake damage occurred on the Campus of Stanford University. The extent of this

destruction was great. The grade of workmanship on the University buildings was of relatively high quality, especially for the older buildings. The original buildings were planned with regard to earthquake possibilities. Steel-frame construction

Fig. 41—Arcade Inner Quadrangle, Stanford University.

on the Pacific Coast was in its infancy at the time, and reinforced concrete almost unknown everywhere, therefore the earliest Stanford buildings and the inner arcades were built by day labor, with heavy cut stone and mortar rich in cement. The outer arcades and buildings, built later, were faced with ashlar and backed with rubble, too often improperly mixed with mortar. The structures built

since 1902 were mostly unfinished in April, 1906, and were made of brick, thinly veneered with stone. A number of them contained some steel framing in domes or roof trusses, which, in vibrating, only helped to throw down the surrounding masonry

FIG. 42—*Rear View Memorial Arch, Stanford University, Showing Arch Ring Intact.*

walls. The earliest structures built remained essentially uninjured, except where they were too high, as in the case of the church and arch, but the latest additions were severely wrecked or destroyed, as they deserved. The central part of the Museum and Roble Hall were built of reinforced concrete, being among the first instances where that material

was used. This construction was uninjured except for the falling of plaster.

I attribute the excessive destruction to three causes: (1), the nature of the ground; (2), the nearness to the fault line, and (3), the type of construc-

Fig. 43—*Fallen Masonry from Top of Memorial Arch, Stanford University, Showing Mortar Strength.*

tion. I consider the third reason by far the most important. Heavy stone-faced buildings of the type we find at Stanford, no matter how well built, cannot resist an earthquake of the intensity experienced at Palo Alto, when we consider the nature of the ground upon which the buildings rest. Top-heavy stone arcades and walls, supported by light masonry pillars, see Fig. 41, are not constituted to

withstand vibration, especially when the roofs are covered with heavy tile. The interior framing, especially of the later Stanford buildings, generally lacks the unity and stiffness which can come only through steel-cage construction or the best type of reinforced concrete cage construction. Considering earthquakes, I do not think the main type of structure at Stanford was happily chosen. The type lacks unity and coherence of frame. The buildings are rigid and often too high. The fault is more in the type of design, and not so much in the execution.

I have seen many pictures of the Memorial Arch showing dramatic destruction. These pictures give a false impression. Fig. 42, a view of the rear elevation, shows that the arch ring itself was not thrown down; in fact, there were but a few cracks in the crown of the soffit. It was the heavy top and cornice, insufficiently tied, that fell, as they should. It would have been surprising had they not fallen. Above the arch was a large box-shaped mass of masonry upon which rested the heavy overhanging cornice, and this box had practically no transverse framing or partition walls of any kind. The masses that dropped from the arch fell in large pieces, nearly 100 feet to the pavement without crumbling, Fig. 43, which proves that the mortar was good. Considerable cement was used in the mortar for the

Memorial Arch. Perhaps not so much, but at least a goodly amount of cement, was used in every building which I examined.

In my opinion, had Stanford's buildings been of reinforced concrete, or of a good type of light brick

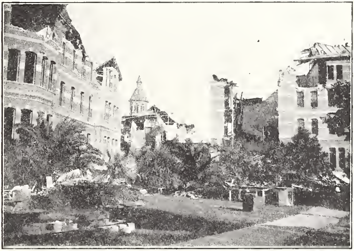

FIG. 44—*View at Agnews Showing the Complete Collapse of the Main Tower of the Asylum.*

or stone construction, bound to a yielding but unified metal frame, there would have been practically no destruction. The type of building should emphasize coherence and lightness, combined with yielding and elasticity. Moreover, it is a mistake to erect university and school buildings more than two stories in height; it is unwise for earthquake

conditions and inappropriate for halls of assemblage.

AGNEWS ASYLUM

Six miles to the north of San José one finds the Agnews Insane Asylum, consisting of one large

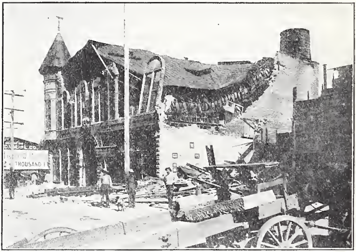

Fig. 45—*Earthquake Destruction, Native Sons' Hall, San José.*

brick, timber framed, building about two city blocks in length, surrounded by some twenty similar but smaller brick structures. One hundred patients and eleven help were killed the morning of the earthquake. I do not know how many were injured. Not one of all these buildings remained habitable. Of all the destruction that I saw, and

I visited the whole disturbed area, this cluster of buildings exhibited the most complete earthquake destruction, with the possible exception of the City Hall buildings in San Francisco. They are both public structures. Is it not time for California

FIG. 46—*A View on First Street, San José, Showing Lack of Framing for First Floor. These Buildings Were Later Pushed Back into Place.*

seriously to realize the situation? The main central brick structure and tower of Agnews Asylum, Fig. 44, entirely collapsed. The central tower fell en masse and crumbled to pieces so that three distinct wings of the buildings, themselves much demolished, were left disconnected. Some of the outer, smaller buildings had nine-inch brick walls

for a height of two stories or more. It is significant to observe that a high water tower of structural steel, situated close to the power house of the asylum, remained entirely intact. The power house, built of brick, and its high brick chimney, collapsed with the rest of the brick structures.

SAN JOSÉ

San José, about forty miles to the south and east of San Francisco, is thirteen miles to the east of the fault line. This city fortunately was spared a conflagration. The earthquake destruction was appalling, as is shown by a few typical photographs; see Figs. 45, 46, 47, and 48.

San José's water works, like that of Santa Rosa, was not injured; its sewers also were left intact, showing that there was no unequal displacement of the ground. The earthquake destruction was the result of severe vibration of poorly constructed brick and stone buildings. Again we find cheap construction with lime mortar, weak framing and insufficient anchoring for floors and roofs. Whole sides and fronts of two and three story store and office buildings on the main business streets collapsed; Fig. 45. On First Street, in the main business center, in one instance, a row of about six or seven buildings careened, due to a lack of sufficient transverse framing in the first story. Stores

occupied these main floors, demanding large window openings and as much floor space as possible. Virtually the upper portions of the buildings rested on stilts; see Fig. 46. Public buildings in San José, with the exception of the postoffice, were

Fig. 47—*Hall of Justice, San José, Completed in 1905.*

generally racked. The tower of the postoffice was thrown down. In too many instances we find heavy stone facings improperly anchored to the interior frames, and roofs without system. In the great area of destruction, one finds roofs depending for their support upon the stiffness of the walls upon which they rested, while from the nature of design and construction the walls lacked stiffness. These

flimsy or clumsy roofs, when subjected to earthquake vibration, tended to lower in the peak and to spread at the ends. Naturally they crushed out the weak outer walls, lacking in bond and inherently weak in mortar. Nearly all the public build-

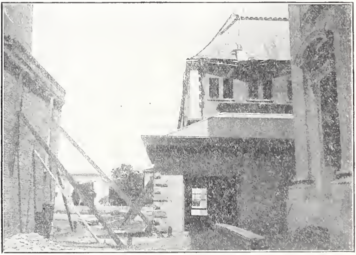

FIG. 48—*Rear View, Hall of Records, San José, Showing How the Heavy Stone Outer Walls Cracked Away from the Interior Framing Due to Improper Anchoring of Walls to Floors and Roof.*

ings, most of the school houses, and many churches in San José, where built of stone and brick, were demolished or severely damaged. Some of these structures still stand, but if wisdom is exercised, most of them will be torn down. Even some frame buildings, notably churches and the annex to the

Hotel Vendome, improperly framed and with weak underpinning, completely collapsed; see Fig. 16.

PÁJARO BRIDGE

The Pájaro Bridge is perhaps the most interesting structural example of violent earthquake effect.

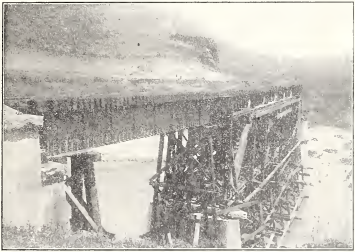

FIG. 49—*Pájaro River Bridge, Southern Pacific Railroad; Temporarily Strengthened by Timber Bents and False Work; View Taken May 30, 1906.*

It is on a six-degree curve whose chord makes an angle of about 40° with the fault line. The fault crosses the bridge near the west end. The bridge consists of two end deck-plate girder spans of fifty feet each, and four intermediate deck Pratt trusses, each of 120-feet span; Fig. 49. The abut-

ments and the intermediate piers are of concrete with granite copings. This structure, in my judgment, would not have been affected by the earthquake had it been at a reasonable distance from the fault line, but it was subjected to a most severe

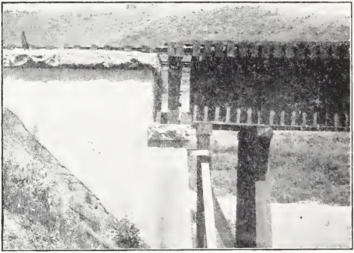

Fig. 50—*West Abutment, Pájaro River Bridge, Southern Pacific Railroad.*

racking, since the ground upon which its piers rested moved unequally. The distance between the end piers was increased 3½ feet. All the piers and abutments were moved more or less, but the heaviest movements occurred at the west end of the bridge. Fig. 50 shows the west abutment where the steel plate girders were moved 24 inches off the abutments and had to be supported by a

temporary wooden bent. The plate girder span resting on this abutment did not fall during the earthquake, although it was dragged off the bridge seat, because it was held up by the rail fastenings and the riveted connections to the next span to the

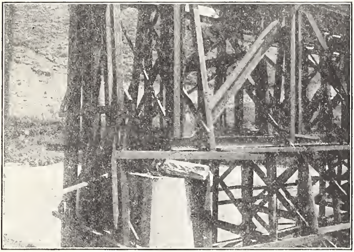

Fig. 51—*First Intermediate Pier, West End, Pájaro River Bridge, Southern Pacific Railroad.*

east. Fig. 51 shows the first intermediate pier at the west end of the bridge. This pier near its base was ruptured in a horizontal section, probably a level between two days' concrete work. The mass of the pier above the rupture was moved eastward about three inches with respect to the base. The coping was ripped from the top and moved

eastward relatively more than 20 inches. The segmental rollers and the steel pedestals upon the coping were smashed and the anchor bolts severely bent. The next intermediate pier leaned somewhat to the east, and the anchor bolts above the coping were bent so that the pedestals of the steel work were moved some three inches. The distortion was less as one approached the eastern end of the structure. The eastern abutment was considerably cracked. The whole bridge superstructure was thrown slightly out of plumb. Earth motions are clearly seen in Fig. 50, where the sloping earth was moved 18 inches along the side wall of the west abutment.

SALINAS HIGHWAY BRIDGE

The Salinas River runs through a marshy district of river deposits of slight elevation above the sea level. Although the region is at a distance of ten to twenty miles from the fault line, there was much evidence of differential surface movement, distinct from elastic vibration, just as in many other instances of soft surface deposits, for example, the San Bruno marsh near South San Francisco, where the Crystal Springs pipe line of the Spring Valley Water Company was so badly ruptured. The land on the south bank of the Salinas River, for a considerable area, was moved into the river in a northerly

direction a distance of about six feet. Fig. 52 shows the south abutment of the Salinas highway bridge. The ground under the superstructure moved about six feet, careening the pile foundations as shown in the picture, without seriously injuring

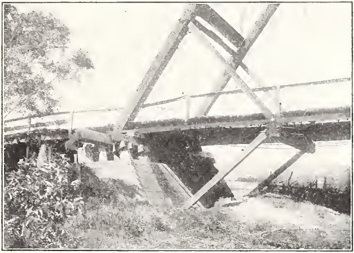

Fig. 52—*South Abutment, Salinas Highway Bridge.*

the trusses. A three-inch oil pipe line which crossed the bridge was ruptured on the south approach, one length of pipe being bent to form the letter "S." The northern approach to the bridge was hardly affected. In fact, the northern bank of the river shows little disturbance at this point. From the Salinas bridge eastward, a distance of about 1½ miles to Spreckels, the south bank of the river is

continuously scarred and rent so that a wagon road was made impassable for vehicles.

THE SPRECKELS SUGAR MILL

At Spreckels is found the Spreckels Sugar Mill. The mill buildings are of excellent construction. The main building, about 100 x 500 feet, a huge box-shaped structure with heavy steel frame, brick walls supported on the frame, and arched concrete floors with steel floor framing, rests on a pile foundation. The mortar for the brick work is excellent and contains considerable cement. Had these buildings been in Santa Rosa or San José, I think they would have stood the earthquake with possibly a few slight cracks and the loss of some brick here and there near the cornices and corners. But unfortunately they rest on soft ground, very much like the made ground areas of San Francisco. Considerable portions of the brick walls were thrown out of the steel frames. The long walls of the main building are supported by steel columns about every 15 feet and are braced transversely at these columns by the interior framing; except in the middle third of the building, where there is an open space from ground to roof to give clearance to the huge machinery. In this middle third, where the long walls are not laterally braced by interior transverse frames and floors, the walls were badly buckled.

Fig. 53—*West Wall, the Spreckels Sugar Mill, near Salinas, Showing Bulged Wall and Brickwork Thrown from the Steel Frame.*

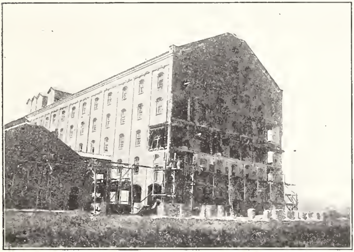

Fig. 54—*North Wall, the Spreckels Sugar Mill, near Salinas, Showing Ruptured Brick Curtain Walls and the Advantages of a Class A Steel Frame.*

The east wall was buckled concave outward, and was badly cracked, but little of it fell. The west wall, in the middle third, was buckled convex outward, and naturally the brick work was thrown down in large masses. Fig. 53 shows the west

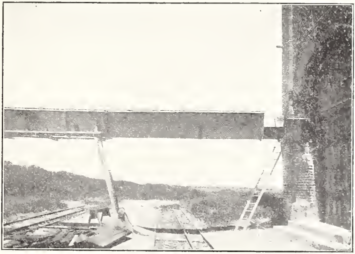

FIG. 55—*Ruptured Conveyor, the Spreckels Sugar Mill, near Salinas, Showing Slipping of the Ground into the River.*

wall of the building. I believe this building was subjected to an earth movement from south to north, which accounts in a measure for the buckling of the long walls in the middle unsupported third. There may have been some settling of the walls also. Large masses of brick in the north wall, Fig. 54, were thrown down. Fig. 55 shows a rupture in the carriage way to the dumps at the south

end of the structure, clearly showing the existence of a decided ground movement at the time of the earthquake. All the smaller buildings were damaged to some extent. The Spreckels Sugar Mill was well designed. It was probably subjected to a more severe racking than any other well designed structure in the State. It can readily be repaired and speaks for the stability of Class A construction.

CONCLUSIONS

There has been much comment of late regarding the relative merits of sea level and lock types of canal for the Isthmus of Panama, in the light of earthquake possibilities. From a study of the earthquake destruction to San Francisco buildings it would appear that honestly, scientifically and generously constructed works can abundantly withstand any reasonably severe earthquake shock so long as the structure does not happen to exist on a fault line or a place of very unequal motions of the ground. On a fault line no structure can fully withstand the shock, no matter how well built. If fortunately located, however, a structure on or near a fault line may not be seriously crippled. In their severe locations it is seen that the 93-foot San Andreas earth dam still fulfills its functions and the Pájaro bridge, though badly crippled, was speedily made usable; the Spreckels Sugar Mill was repaired

without great expense, and large well built buildings on honestly designed and deep foundations stood the racking on the made ground in San Francisco. In the future, water supply conduits should avoid fault lines, marshes, and other unstable ground whenever possible. Dams should not cross fault lines, and when possible should not be run at right angles thereto; yet considering their purpose it usually will be necessary to place dams in the most unsatisfactory positions. It is not wise in earthquake countries to build bold arch dams of thin construction. Important railway bridges should be located at river crossings not coincident with lines of crustal weakness, and should avoid soft alluvial deposits. It is easy to state this advice and these restrictions, but it is another thing to follow them. The locating engineer is not always free to choose his site. Where structures must be built upon treacherous ground or near fault lines, no expense should be spared for good materials, high grade workmanship, and intelligent design. The most generous factors of safety should be used and the best designing talent employed. California engineers can not pay too much attention to geologic structure.

Careful examination of all types of structures within the earthquake belt leads me to emphasize the following detailed conclusions. I do not expect

every one to agree with them. Some of the statements may be very radical, and some may be wrong:

1. Cornices and top walls of buildings, especially of brick and stone structures, should not be heavy nor have great projection. In the future cornices and top walls should be more securely anchored with metal, their masonry bond should be made with care and the cementing materials should be of high quality. A considerable number of lives were lost by falling brick and stone from such sources. These parts of buildings have been very generally demolished by the earthquake.

2. Cornices and top walls of first class steel cage constructed buildings, where the steel framing and anchoring has been carried into the cornice work, have resisted the earthquake.

3. Projecting brick work and fire walls of ordinary brick and stone structures have proven themselves an abomination, especially where lime mortar was used. With cement mortar the destruction was nearly as great, the only difference being that the material fell in large masses.

4. Brick chimneys for ordinary brick or frame dwellings should be built of weak lime mortar above the roof line. This seems a paradoxical statement. In a severe earthquake the brick chimney will not move with the house. It must col-

lapse. If built with rich cement mortar it will fall fall in one piece and crush through the roof. If built of lime mortar it will crumble and the individual bricks will roll off the sloping roof. Metal chimneys should be studied for the part above the roof line. If brick is insisted upon from preference or custom, reinforce the brickwork with steel rods and bands.

5. Terra cotta and similar materials should not be used so profusely and boldly in the future. They are not good earthquake materials. They have been badly cracked by earthquake vibration. The north wall of the Fairmont Hotel, where it is faced with terra cotta, was badly cracked. Pressed brick work with good mortar and good bond is a far more satisfactory material. Terra cotta ornamentation on the Mills Building and many other buildings was badly spalled by vibration. I would not eliminate terra cotta from use, but it should be less highly ornamented, be manufactured with greater thickness, and the hollows should be filled with a cementing matrix.

6. Hollow tile partitions in the General Postoffice were almost wholly destroyed by the earthquake. Of course this building rested upon very treacherous ground, but the earthquake certainly did very much more damage to tile partitions in San Francisco than is generally admitted. These

partitions have little strength and are readily collapsible. They have no elastic continuity.

7. I believe hollow tile floors were less disturbed by the earthquake than tile partitions, because there was less tendency to unequal motion in the plane of the floor; whereas partitions were subject to a greater racking motion. Tile partitions and floors do not appeal to me with the same force as reinforced concrete construction, especially when the question of fire-proofing is left out of the discussion.

8. Brick buildings without steel work and of light construction should have small height, three to four stories at most. Their bond of brick work should be carefully inspected and their brick walls should be securely tied to the floor and roof frames. On soft ground their foundations should be even more carefully designed for stiffness of framing and distributing power than those for wooden buildings. The bond of brick work in San Francisco was proverbially bad.

9. Cheap lime mortar should not be allowed for buildings in the congested districts of San Francisco. Cement with just enough lime to make it workable—say one part cement to four or five of lime mortar—should be more generally insisted upon, not only in the congested parts of the cities, but everywhere where brick buildings are used.

The high school building at Berkeley may be taken as an example of lime mortar building. It was most seriously cracked, especially in the second story. Hundreds of buildings might be named in this connection. In the light of what has happened it is a crime to use bad bond and lime mortar for brick work in schools and public buildings, in fact in all buildings. Mortar has been too generally applied to dry brick.

10. Brick buildings of greater height than four stories should have heavy walls and a sufficient number of interior cross walls to give lateral stiffness. The Appraiser's Building or Custom House was unharmed by the earthquake. The Palace Hotel stood the shock splendidly, the latter being an excellent type of brick structure, whose brick walls were reinforced with iron rods. The foundations of such buildings should be designed with the greatest care to prevent unequal settlement.

11. All over the earthquake belt one found brick and stone structures badly demolished by the falling out of main walls due to improper design of the roof trusses. These trusses too generally were of clumsy wood construction improperly anchored to the supporting walls and unscientifically framed. Too generally they were lacking in a lower chord tension member. The earthquake caused such roofs to spread and kick out the walls, which had no

ability whatever to resist a lateral thrust. The high school building in Berkeley is a typical example. For large school buildings roof trusses of steel should be used. One saw many cases where brick walls stood the shock that would have been thrown down except for the tying property of the roof trusses above them. The Majestic Theatre in San Francisco clearly showed how steel trusses kept high walls from collapsing.

12. Properly constructed wooden buildings withstood the earthquake with the exception of their brick chimneys, no matter where located in the earthquake belt, except on the fault line and in regions of the greatest disturbance on soft ground. Some frame buildings collapsed upon favorable ground due to improper underpinning. There should be more continuity in the frames of wooden buildings, especially at the floor levels, and the underpinning should be more carefully attended to in the future.

13. At the time of the earthquake there were entirely too many top-heavy and improperly braced brick and stone towers and steeples in San Francisco and other cities. Where they are merely ornamental, mere masonry, towers should be discouraged as far as possible. Their ruins were everywhere to be seen in San Francisco, Oakland, Santa Rosa and San José. The Ferry tower might

have had heavier framing, although it should hardly be spoken of in this connection. Most towers lack in interior cross walls and in necessary steel frames. The Memorial Arch at Stanford University has been referred to. Reinforced concrete, where not too boldly employed, is well adapted for these purposes.

14. Important buildings like the Postoffice should not be placed on filled ground or treacherous ground, but when they must be so placed, they should have heavier steel framing and lighter masonry work than the Postoffice. The type of building structure to be selected in these cases should be determined by the nature of its foundation site. Remarks which I have made concerning buildings at Stanford University are here pertinent.

15. High buildings with deep pile foundations of the proper design withstood the earthquake shock well on soft ground. Considering the nature of the material on which the Ferry Building rests, it stood the shock splendidly because of its excellent pile foundations. The Call Building foundation represents the slab type, apparently equally well fitted for service.

16. Reinforced concrete cage construction should be more respected in the future by the building laws and trades unions of San Francisco. There is no reason why buildings of this type, designed

by competent engineers, should not be at least six or eight stories in height.

17. Low buildings of intelligent reinforced concrete construction are far more able to resist earthquake shock than brick and stone buildings.

18. On soft ground the footings of ordinary buildings too light to require pile foundations might have cellar slabs of reinforced concrete to act as units with the wall footings to give distributing power and prevent unequal settlement.

19. Reinforced concrete sewers should be studied in the light of brick sewer destruction in the made ground of San Francisco.

20. Important water mains should avoid soft ground and when they must necessarily pass from firmer to softer ground they should be provided with flexible joints and cut-offs.

21. Important water mains on which the fire service depends, which must run through the made ground of the city, should be of riveted wrought iron or steel, have flexible joints at intervals and be lodged in tunnels, say of reinforced concrete. Earthquake disturbance near the water front might severely crack such tunnels without great injury to the pipes within, due to the properties of the materials, the nature of the pipe joints, and the clear space between the tunnel walls and the pipe. Such a construction would further give more

probability of access to the pipe in case of calamity. Important networks of pipes in the gridiron system should be arranged in more or less independent units with respect to the softer and firmer grounds of the city; so that flow in the pipes on made ground could be quickly separated from that on more solid foundations.

22. Main conduits running from storage reservoirs to the city should avoid marshy lands as far as possible. Where they must necessarily cross swamps and marshes, they should be provided with flexible joints and not be too firmly blocked to their platforms.

23. The city should have a number of sources of supply in widely separated localities of distinct geological formation.

24. Equalizing reservoirs within the confines of the city should be numerous and of considerable capacity.

25. Small distributing reservoirs within the city limits should be connected with the main conduits by large pipes independent of the gridiron system. These pipes should be carefully designed and be easy of access. With such provision, some of the delay incident to the forcing of water through crippled street mains to the various city reservoirs and pumping stations might have been avoided. Arte-

sian wells should be encouraged as local sources of supply.

26. The business district should be safeguarded by a salt water system in addition to the regular water supply for fire service, and where salt water pipes must run through made ground they should be provided with flexible joints and with a tunnel construction as has been suggested for the main water pipes; or they should be on the surface.

27. San Francisco needs a fire boat service.

28. High brick chimneys for factories should be built with cement mortar; even then they should be reinforced. In many cases a lower chimney with a forced draft should be considered. A study of reinforced chimneys should be made. They would withstand earthquake shocks much better than brick ones.

29. In the business section of the city Class A buildings and first class reinforced concrete structures should be encouraged at the expense of Class B structures, and the skimping of steel frames should meet with entire disapproval. Diagonal framing should be introduced wherever windows and interior passage ways or openings do not prevent; better still, heavy knee braced framing and spandrel girder framing should receive more attention.

30. The design of high buildings with self-supporting walls should be discouraged.

31. Steel columns should run through more than one floor, and their splice joints should be strongly designed.

32. Cast iron columns should not be used.

33. Heavy stone ornamentation should not be hung to the steel frames of high buildings, and heavy centralized supports on the first floor, as in the Flood Building, should be avoided when possible. No expense should be spared for foundations of buildings of great height.

34. Heavy stone corner piers at the sidewalk level of steel framed buildings should rest upon the frame and not upon masonry walls under the sidewalk. Where such piers rested upon concrete under the sidewalk, the stone work was badly cracked; where they were supported by the steel frame no cracks were found.

35. Face brick should be carefully bonded to the back brick in Class A buildings. Large areas of face brick fell from the west wall of the Merchants Exchange Building because of improper bond.

36. Reinforced concrete buildings of careful, honest, and intelligent design should be allowed to enter competition in San Francisco. It is unfortunate that reinforced buildings have been placed in the Class B list. To the layman this implies

inferiority to Class A structures. Of their types Class A buildings are not to be considered better than first-class reinforced concrete cage constructed buildings, only I should not use the latter type for structures of the greatest height.

37. Neglecting the problem of surface appearance, Class A buildings might be designed with curtain walls of reinforced concrete instead of using brick and terra cotta.

38. High buildings like the Mills Building in which the floors are supported on a steel frame, but whose walls are self-supporting, should not be imitated in design in the future. When such buildings are badly shaken, or when their outer walls are badly damaged, repair is difficult. In Class A buildings, where the steel frame carries the load of each floor independently, such difficulty vanishes. The Mills Building had the further miserable feature of columns breaking joints at every floor.

39. Electric insulation for high tension transmission should be rigorously inspected. Chimneys on cheap brick and frame dwellings should be more sensibly built. Electric wires and bad chimneys were fruitful sources for the starting of fires immediately after the earthquake.